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Original Article

Pseudo-Static Loading Investigation on the Performance of Steel Frame with and without STRP Bearings as the Base Isolation Material

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Abstract - *The investigation evaluates the performance of the steel frame subjected to pseudo-static loading with a fixed base and STRP base. The technology of seismic base isolation is flourishing in developed countries because of its efficiency in resisting seismic vibrations. Scrap Tyre Rubber Pad (STRP) bearings shall be an alternative to conventional seismic base isolation techniques with an affordable cost for a developing country. The properties of the STRP's are quite equivalent to conventional rubber bearings. Researchers have undergone numerical, analytical studies pertaining to STRP bearing for buildings and have suggested that it be used for low-rise regular buildings and have given superior results. Based on the results of analytical studies, an attempt to investigate the performance of the STRPs in a scaled-modelled steel frame structure has been conducted. The experiment was conducted to evaluate the performance of the steel frame with and without STRP bearings. The ultimate aim of this paper is to examine the sliding property of the STRP's placed in the frame. For this aspect, for the lateral seismic loading applied, the deflections of the frame at the top, intermediate and at the bottom stories have been studied. From the investigation, it is observed that the deflections of the frame are greater at the roof compared to other stories. Significantly, from this study, it is reported that an increase in displacements of about 38% to 40% is attained for the frame using STRP bearing for base isolation.*

Keywords - *STRP, LVDT'S, Deflection of stories, Load.*

1. Introduction

The seismic response of structures during earthquakes has long been a concern for engineers and researchers seeking innovative methods to enhance their resilience. One such technique gaining attention is the use of isolation systems, particularly those incorporating waste rubber materials (Makris 2018), (Carpani 2017) and (Nanda 2015). These systems aim to minimize the impact of ground motion on structures, thus reducing potential damage (Zhou et al., 2004).

Isolation techniques involve inserting flexible bearings or isolators between a building's foundation and superstructure. These isolators, often made from waste rubber derived from discarded tires, allow the building to move independently of the ground's motion during an earthquake (Buckle et al., 1990), (Melkumyan 2014), (Islam et al., 2011), (Bayraktar et al., 2012) and (Boardman et al., 1983).

This movement decouples the structure from the damaging effects of seismic waves, effectively mitigating the forces transferred to the building. The waste rubber-based isolators possess several advantageous characteristics. The inherent elasticity and damping properties of rubber make it an excellent material for absorbing and dissipating seismic energy (Skinner et al., 1993). Moreover, using waste rubber promotes environmental sustainability by repurposing discarded materials that might otherwise contribute to pollution. This aligns with the growing emphasis on eco-friendly construction practices. Spyrakos et al. (2009) and Pitilakis et al. (2015) investigated the effects of soil-structure interaction on the seismic response of base-isolated structures. They developed improved modeling techniques to account for these interactions.

Omkar et al.(2020) studied the performance of multi-storey RC-framed regular and irregularly shaped buildings installed with rubber isolators and subjected to time history analysis. From the study, the authors concluded that there is an increase in time of about 1.6 times with base isolation in the buildings.

Kumar et al. proposed and developed STRP bearings from used recyclable automobile tyres of size 200 mm x 200 mm x 130 mm. The authors performed preliminary axial loading and shear tests on the specimen. As a result, the authors reported that the STRP bearings could withstand compressive stress up to 4 MPa (Kumar et al., 2019) and (Mishra et al., 2012).

Turer and Ozden (2020) have used discarded automotive tyres in studies to build low-cost seismic base isolation pads. Experimentally, the mechanical and dynamic properties of STRP specimens constructed from several tyre brands, with varying numbers of layers and orientations, were assessed. These STRP tests were compared to each other as well as a commercially available Laminated Rubber Bearing (LRB) specimen, and lastly, concluded that there they used waste discarded material and it is environment friendly. The outlay of the study is to experimentally investigate the steel frame subjected to static loading with and without STRP bearings and to experimentally investigate the steel frame subjected to static loading with and without STRP bearings (Turer and Ozden, 2020).

The application of base isolation has been explored for various structural systems, including bridges. Kunde and Jangid (2003) provided a state-of-the-art review.

On the seismic behavior of isolated bridges, discussing the challenges and considerations specific to bridge structures [17]. Several experimental studies have been conducted to investigate the seismic performance of base-isolated structures, including steel frames[18]. The report by Constantinou et al. (2007) evaluates the performance of seismic isolation hardware under service and seismic loads. Numerical Simulations and Parametric Studies: Numerical simulations and parametric studies have been carried out to evaluate the influence of isolator characteristics, such as stiffness, damping, and period shift, on the seismic response of base-isolated structures. The Paper by Matsagar and Jangid (2004) investigates these aspects and highlights the importance of proper isolator selection for optimum performance [19].

The behaviour of structures equipped with waste rubber isolators is complex and involves a combination of mechanical principles, material properties, and structural dynamics. Researchers use advanced computational models and physical testing to simulate and analyze the seismic response of isolated structures. The effectiveness of the isolation technique is measured by parameters such as peak accelerations, inter-story drifts, and residual displacements. Eventually, the seismic response of structures using isolation techniques with waste rubber presents a promising avenue for earthquake engineering (Chiaro et al., 2019).

By incorporating flexible isolators made from discarded rubber materials, these systems enhance a building's ability to withstand seismic forces and minimize potential damage. As research in this field progresses, a deeper understanding of the behaviour of such systems will undoubtedly lead to safer and more resilient infrastructure in earthquake-prone regions. The objective of this research is to determine the load-bearing capacity of the frame subjected to earthquake load with and without STRP bearings, to determine the stiffness degradation of the frame subjected to earthquake load with and without STRP bearings and to determine the energy dissipation capacity of the frame subjected to earthquake load with and without STRP bearings.

Seismic base isolation is an effective technique for mitigating the adverse effects of earthquake ground motions on structures. By decoupling the superstructure from the horizontal components of ground motion, base isolation systems can significantly reduce the seismic forces and deformations experienced by the structure. Among the various base isolation devices, elastomeric bearings, such as Steel Rubber Bearing Pads (STRP), have gained widespread acceptance due to their practical and economic advantages. Numerous studies have investigated the seismic performance of base-isolated structures using numerical simulations and experimental testing. However, most of these studies have focused on reinforced concrete or composite structures, with limited research on the behavior of base-isolated steel frames.

Steel Structures possess unique characteristics, such as lower inherent damping and different failure modes, which necessitate dedicated investigations. Several researchers have evaluated the seismic response of base-isolated steel frames through numerical simulation. While these studies have provided valuable insights, they often rely on simplified assumptions and models, which may not accurately capture the complex behavior of base isolation systems under severe ground motions. Experimental investigations on the seismic performance of base-isolated steel frames are scarce, particularly those involving pseudo-static loading tests.

Pseudo-static loading tests offer a controlled and cost-effective approach to simulating the effects of earthquake ground motions on structures. These tests allow for the application of increasing lateral loads while monitoring the structural response, providing valuable data for evaluating the performance of base isolation systems and calibrating numerical models. This research aims to bridge the existing knowledge gap by conducting an experimental investigation on the seismic performance of steel frames with and without STRP bearings as the base isolation material. The novelty of this work lies in the use of pseudo-static loading tests to evaluate the seismic response of base-isolated steel frames, a topic that has not been extensively explored in the literature. Through a comprehensive experimental program, the study seeks to quantify the effectiveness of STRP bearings in mitigating seismic forces and deformations in steel frames. The research findings will contribute to a better understanding of the behavior of base-isolated steel structures and provide valuable data for validating and improving numerical models used in seismic design.

2. Methodology

2.1. Preparation of the Steel Frame

In this paper, a G+4-storey steel frame (Guerrero et al., 2016), scaled down to 1/10th, has been used for the investigation. The structure is 1.45 m high, 0.6 m wide and depth 0.3m. The steel plate is made up as per ASTM a- 36, which is EN S275 steel plate as per IS 2062:2011 code (IS 2062:2011).


(a) (b)

Fig. 1 Steel frame (a) Fixed base, and (b) STRP base.

The yield stress of the steel used for the study is 250 MPa. The columns are rectangular sections with a cross-sectional area of 243.84 mm2. The cross-sectional area of the beams along the x-direction is 660.67 mm2, which is the profile of the T section. Subsequently, the beams along the y-direction have a cross-sectional area of 303.60 mm^2 which is of rectangular profile. The model steel frame has been prepared, as shown in Figure 1 and applied for the experimental investigation. Figure 1(a) and Figure 1(b) shows the steel frame with and without STRP bearings, respectively.

2.2. Casting of the Foundation Block

In the second phase of the research, a foundation block was cast, as shown in Figure 2. The grade of the concrete used is M 30 grade (IS 10262:2009), the volume of the foundation is 0.139 m^3, and the height and the diameter of the foundation block are 0.305 m and 0.762 m, respectively. The mix design has been conducted as per IS 10262:2016, and the quantity of the ingredients, such as cement, fine aggregate, coarse aggregate and water, arrived as m 94.85 kg, 79.037 kg, 153.14 kg and 42.68 litres, respectively. The foundation has been cured for 28 days so that when lateral seismic loading is applied, failure of the foundation block is neglected. The foundation block acts as the fixed base for the steel frame to prevent excessive deflections in the frame during loadings.

Fig. 2 Foundation block casting

2.3. Preparation of STRP Bearing

Scrap tyres are obtained from the landfills of Avadi town, Chennai. The selection of the tyres for the preparation of STRP bearings is automobile truck/ bus tyres. The tread part of the tyre has been used for the preparation of STRP bearings, as shown in Figure 3. As proposed by the researchers, the appropriate dimensions are taken. In this current research, the bearings are scaled to accommodate the frame. The tyre scraps are cut into suitable sizes, arranged in 6 layers, and packed together using adhesives. The design of the STRP bearings is to be carried out as per UBC-97 design principles (UBC-97), and the size of the bearing used is 200 mm x 180 mm x 46 mm (Shirai and Park, 2020). Most exclusively, the dynamic properties are satisfactory, as analysed and reported by the previous research (Pillai, 1995). It is to be noted that these types of bearings shall be utilised in high seismic risk zones but restricted to 19.2 m as per ASCE-7-05 code conditions (ASCE:7-05) and (IS:1893-2016). The efficiency of STRP bearings is tested analytically, and therefore, the bearings are to be tested experimentally.

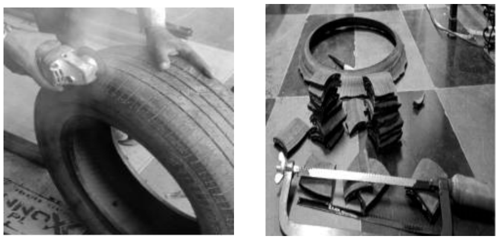
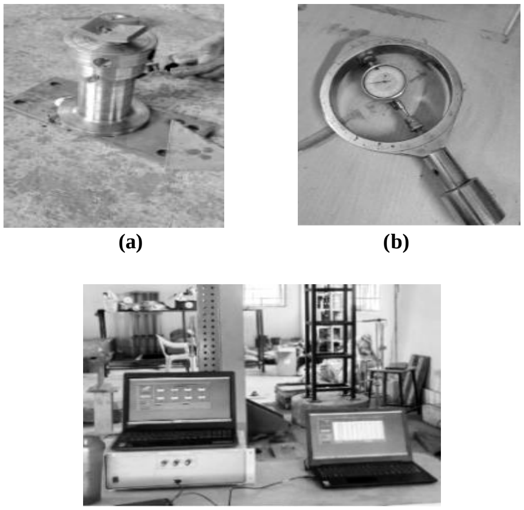

(a) (b)

Fig. 3 Scrap tyres (a) Cutting of scrap tyre, and (b) Preparation of STRPs.

2.4. Experimental Investigation

The steel frame is fixed to the foundation block with the fixed base, as shown in Figure 1(a) and the STRP base, as shown in Figure 1(b). A 5-ton screw jack, as shown in Figure 4(a), is used for the research. For the application of loads, a proving ring of capacity 50 kN has been utilised for the research, as shown in Figure 4(b). LVDTs are placed at the top and the intermediate stories of the frame and connected to the data acquisition system, as shown in Figure 4(c).


(a) (b)

(c)

Fig. 4 Equipments for the study (a) Jack, (b) Proving ring, and (c) Data acquisition system.


Fig. 5 Frame connected with jack and proving ring

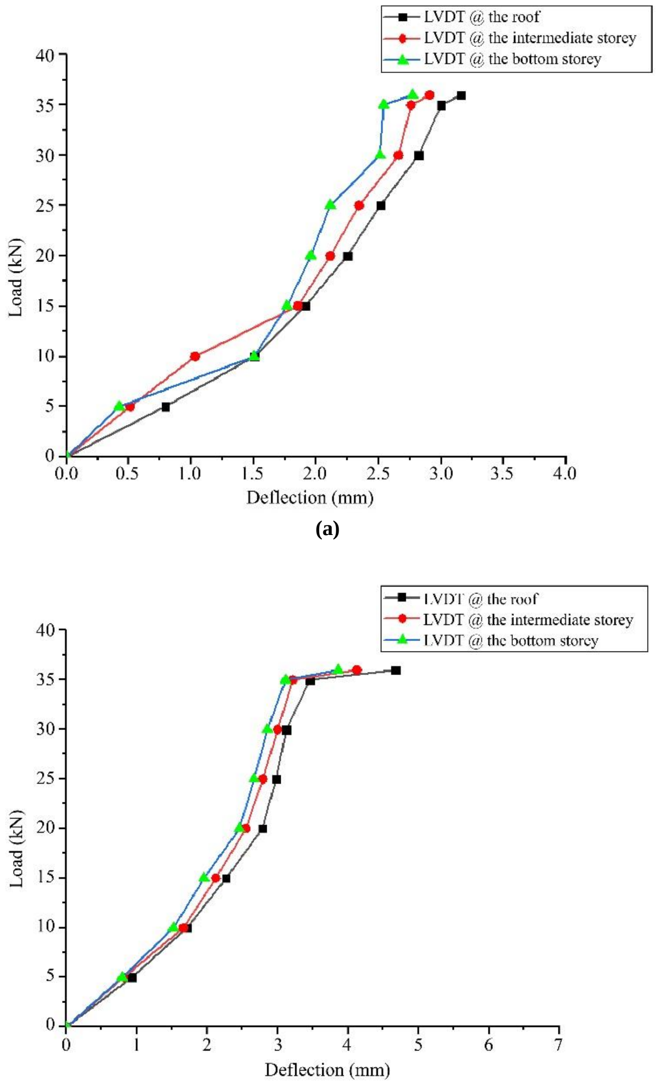
The LVDTs are connected to the data acquisition system, as shown in Figure 5. The data acquisition system accurately read the values of deflections observed in the frame at three different locations such as at the roof, intermediate and bottom storey. The jack is fixed firmly to the loading frame, and extensively, the proving Ring is connected and subsequently connected to the frame. Load is applied gradually from the screw jack, and the corresponding deflections are measured in the LVDT's. As the capacity of the screw jack is 50 kN, the Load is limited to 40 kN. In the first series of tests, the frame is of fixed base condition. Load is applied, and the respective deflections are determined in the LVDTs. The respective load deflection graphs are plotted and shown in Figure. For fixed condition. Subsequently, the STRP bearings are placed at the four bases of the frame as Load is applied using the screw jack, and the corresponding deflections are measured in the LVDT's.

3. Results and Discussions

The behaviour of the frame pertaining to static loading was studied. The deflections of the frame with three LVDTs placed at the roof, intermediate and bottom stories are studied. The capacity of the proving Ring is 50 kN. So based on the results, Load vs. deflection graphs (as shown in Figure 6) are plotted and the deflections at the different locations of the frame have been investigated. The maximum deflection of the frame with a fixed base and STRP base has been studied at each LVDT point. From the investigation, it is observed that maximum deflections occur at the roof in both fixed and STRP bases. Subsequently, higher deflection exists in the intermediate storey compared to bottom stories and the same kind of results are seen in previous studies (Aydin et al., 2012) and (Chanda and Debbarma, 2020). For a 5 kN load, in the case of LVDT 1 (roof), for instance, the deflection of the frame increases from 0.798 mm to 0.931 mm with an STRP base. Similarly, for the intermediate storey (LVDT 2), the deflection of the frame increases from 0.512 mm to 0.823 mm with STRP base and subsequently, with respect bottom storey (LVDT 3), an increase in deflection from 0.422 mm to 0.791 mm is observed with STRP base. The storey displacements of the frame with and without STRP bearings are listed in Table 1.

Table 1. Storey displacements of the frame with and without STRP base

Load (kN)	LVDT 1 (at the Roof) (mm)	LVDT 2 (at the Intermediate Level) (mm)	LVDT 3 (at the Bottom Storey) (mm)
Fixed Base			
0	0	0	0
5	0.798	0.512	0.422
10	1.502	1.034	1.502
15	1.912	1.851	1.765
20	2.248	2.111	1.956
25	2.512	2.342	2.112
30	2.82	2.668	2.512
35	3	2.761	2.541
36	3.158	2.914	2.772
STRP Base			
0	0	0	0
5	0.931	0.823	0.791
10	1.713	1.661	1.521
15	2.266	2.121	1.953
20	2.782	2.546	2.455
25	2.977	2.789	2.665
30	3.122	2.999	2.854
35	3.451	3.213	3.111
36	4.677	4.123	3.857



(a)

(b)

Fig. 6 Static loading at different locations of frame (a) Fixed base, and (b) STRP base.

An anticipated increase in displacement is ultimately observed with the STRP base at all the levels of LVDTs. The conceptual idea in seismic isolation is that the cause of increased displacement indicates the superior attainment to facilitate the sliding motion of the isolator during seismic action. Therefore, the isolator in this investigation, the STRP isolator, accomplishes the ability to slide during earthquakes due to its increased displacement seen in critical points of the frames.

Based on the data presented in the table, it appears that the steel frame with STRP bearings as the base isolation material exhibited better performance compared to the fixed-base steel frame configuration. The key observations and potential reasons for the improved performance are as follows:

1. Lateral displacements:

- For a given lateral load, the lateral displacements measured by LVDT 1 (at the roof), LVDT 2 (at the intermediate level), and LVDT 3 (at the bottom storey) are consistently higher for the STRP base-isolated frame compared to the fixed-base frame.
- This behavior is expected because the STRP bearings introduce additional flexibility at the base, allowing for larger lateral displacements while reducing the seismic forces transmitted to the superstructure.

2. Increased flexibility and energy dissipation:

- The larger displacements observed in the STRP base-isolated frame suggest that the bearings effectively decoupled the superstructure from the horizontal ground motion, leading to increased flexibility and energy dissipation through the deformation of the bearings.
- This increased flexibility and energy dissipation capacity contribute to mitigating seismic forces and reducing the demand on the structural members, potentially enhancing the overall seismic performance of the frame.

3. Reduced interstory drifts:

- Although the lateral displacements at the roof level (LVDT 1) are higher for the STRP base-isolated frame, the displacements at the intermediate level (LVDT 2) and the bottom storey (LVDT 3) are generally lower compared to the fixed-base frame.
- This observation indicates that the STRP bearings effectively distributed the lateral displacements more uniformly along the height of the frame, potentially reducing the inter-story drifts and associated damage to the structural members.

4. Improved seismic performance:

- The increased flexibility, energy dissipation capacity, and reduced interstory drifts observed in the STRP base-isolated frame suggest an improved seismic performance compared to the fixed-base frame.
- The base isolation system effectively mitigated the seismic forces and deformations experienced by the superstructure, potentially enhancing the overall structural safety and serviceability under seismic loading conditions.

These findings align with the expected benefits of base isolation systems and demonstrate the effectiveness of STRP bearings in enhancing the seismic performance of steel frames. However, it is essential to note that the specific performance improvements may depend on various factors, such as the bearing properties, frame geometry, and loading characteristics. Compared to state-of-the-art techniques reported in the literature, the use of STRP bearings as base isolation material for steel frames offers several advantages:

1. Cost-effectiveness: STRP bearings are generally more economical compared to other base isolation systems, making them an attractive option for practical applications.
2. Simplicity of design and construction: The implementation of STRP bearings is relatively straightforward, reducing the complexity of design and construction compared to more sophisticated base isolation systems.
3. Versatility: STRP bearings can be adapted to various structural configurations and loading conditions, providing flexibility in their application to different types of steel structures.
4. Experimental validation: The present study provides experimental evidence and data to support the effectiveness of STRP bearings in enhancing the seismic performance of steel frames, which is often lacking or limited in existing literature.

While numerical simulations and analytical studies have been conducted to investigate the behavior of base-isolated steel structures, the experimental data obtained in this research can contribute to the validation and improvement of numerical models, further advancing state of the art in this field.

4. Conclusion

The use of recyclable tyre bearing (STRP) could play a crucial role in the installation of seismic isolation in an environmentally friendly manner. Regardless of the cost, the modern world aims to lessen the impact of seismic disasters. The adoption of conventional base isolation methods is quite difficult and costlier for a developing nation to implement.

Therefore, the alternative method of using STRP bearings shall effectively affordably reduce seismic vibration. From the investigation, it is observed that an increase in displacement of about 1.23 times to 1.47 times is attained with the STRP base compared to a fixed base. Therefore, this enhances the improvement of the time by about 40 to 50% with the STRP base isolator.

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