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Suspension Type Base Isolation: For Seismic Impact Mitigation in High-Rise Buildings

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Abstract

Suspension Type Base Isolation (STBI) is a system where the base of a structure is literally suspended using suspenders. With STBI innovative design and construction, significant reduction in seismic impact could be achieved in all heights of structures from low-rise, mid-rise, to high-rise ones. The significant reduction in impact can be observed in reduced structure's displacement, acceleration, and base shear of structure during earthquake events. The structural and mechanical design of the STBI is especially suited for high-rise structures. This new innovative system can handle uplift forces on columns caused by relatively large overturning moments in high-rise structures during seismic events. Most seismic isolators in use presently are not applicable for high-rise buildings. STBI is capable of mitigating seismic impact as could be observed in reduced structural displacement and acceleration by around 88% as compared to fixed-base structure even in strong earthquake events. Simply stated, if the earthquake intensity, for instance, is around 9, the structure will "feel" around intensity 5 only. Another ideal feature of STBI is its ability to allow the structure to sway back to its original position after every seismic event. This is called auto-centering which is initiated by the pull of gravity.

Keywords: seismic isolators, base-isolation, friction pendulum bearing, lead-rubber bearing, steel moment frame building, base shear

1. Introduction

Earthquake is one of natural phenomena that has been causing extensive damages to lives and properties, worldwide. A saying goes that earthquake does not inflict harm on living organisms, but collapsed structures do. Hence, experts all over the world have been finding solutions to, at least, mitigate the impact of earthquake on structures. Structural codes have been written and rewritten to guide engineers and architects design and build structures that are seismic resistant. Several devices have been developed and invented to achieve this goal of mitigating or reducing the damages caused by earthquake. These devices include dampers and base isolators among others. In base isolation, devices are installed between the ground, via foundation, and the base of the structure. When the ground shakes, the structure will not shake in the same intensity as the ground. The structure's shaking is much reduced than the ground's shaking.

2. Present types of seismic isolators

Base isolators commonly used in engineering and construction practices at present are the bearing types. These isolators include Lead Rubber Bearing [8] (Figure 1) and Friction Pendulum [9] (Figure 2) among others. Although bearing type isolators (BTI's) show promise in mitigating seismic impact, yet, their applications have disadvantages.

2.1. Disadvantages of BTI's

Studies conducted by several researchers prove effectiveness of BTI's in reducing devastating impact of earthquake on structures, but there are some disadvantages observed in them. Lead in LRB is toxic [1]. Rubber tearing can cause LRB's eventual failure [2]. Other observer mentioned about rubber hardening [3]. LRB becomes ineffective in elevated intensities [4]. Friction Pendulum sliding surfaces may deteriorate over time that might lead to inconsistent performance. In this study, only two limitations are covered below.

2.1.1. Not for high-rise structures with high aspect ratio. This limitation of bearing type isolators can be attributed to their mechanical constructions. Construction of LRB (Figure 1) [8] is basically a stacking of relatively thin steel sheets with rubber spacers in between. This kind of construction can only resist compressive forces, not tensile forces. The construction of Friction Pendulum (FB) [9], as shown in Figure 2, includes sliding curved surfaces. It can be noticed that major components are stacked-up one-after-another. The arrangement of parts indicates that the said isolator is also strong in resisting compressive forces, yet it cannot handle uplift forces.

Figure 1: Lead Rubber Bearing Design

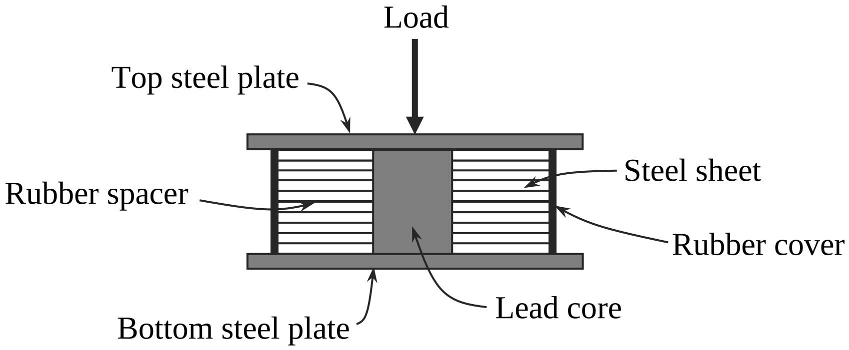
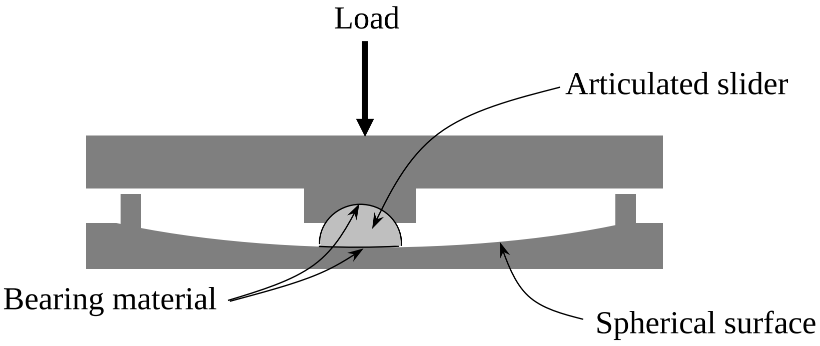


Figure 2: Friction Pendulum Design



To explain this issue, consider Figure 3 that shows a model of structure implementing Lead Rubber Bearing (LRB). When the overturning moment (OM) is relatively large, as in the case of high-rise buildings under strong ground shaking, the reaction acting on the left LRB is tension (uplift), a condition that this seismic isolator cannot handle. Similar issue is also faced by Friction Pendulum (FP) isolators (Figure 2). The fact that BTI's are incapable of resisting tensile forces is the very reason why they are not applicable to high-rise buildings in mitigating seismic impact. Hence, application of these isolators is limited only to low-rise and mid-rise structures with low aspect ratio.

Figure 3: LRB under Tension or Uplift Force

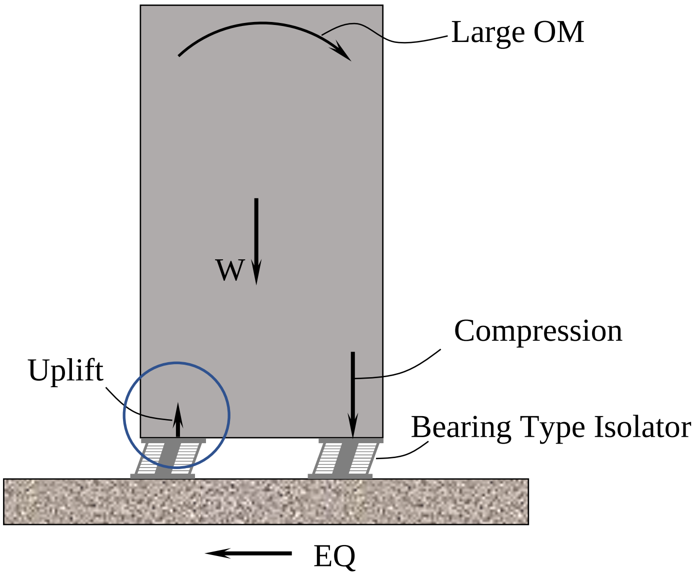


Figure 4: LRB after Earthquake

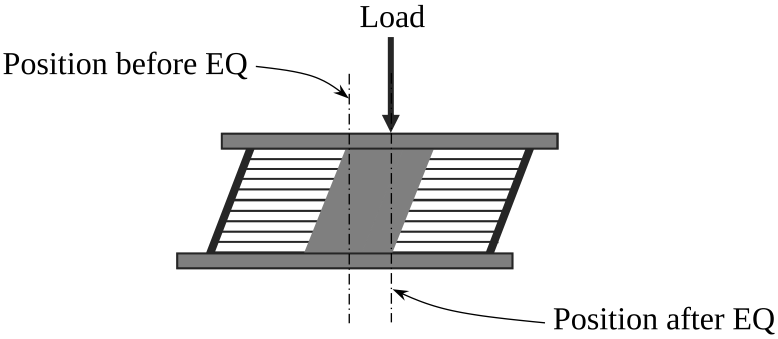
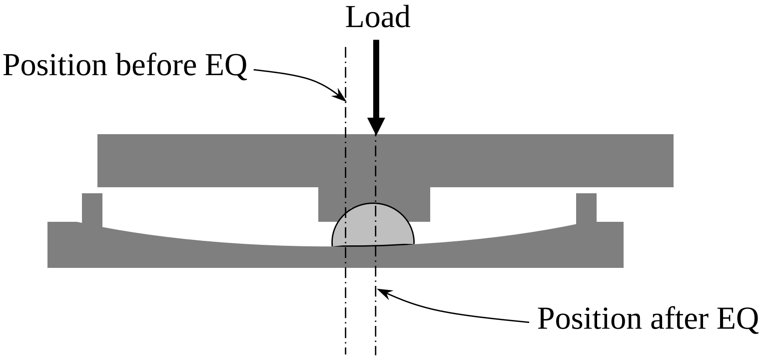


Figure 5: Friction Pendulum after Earthquake

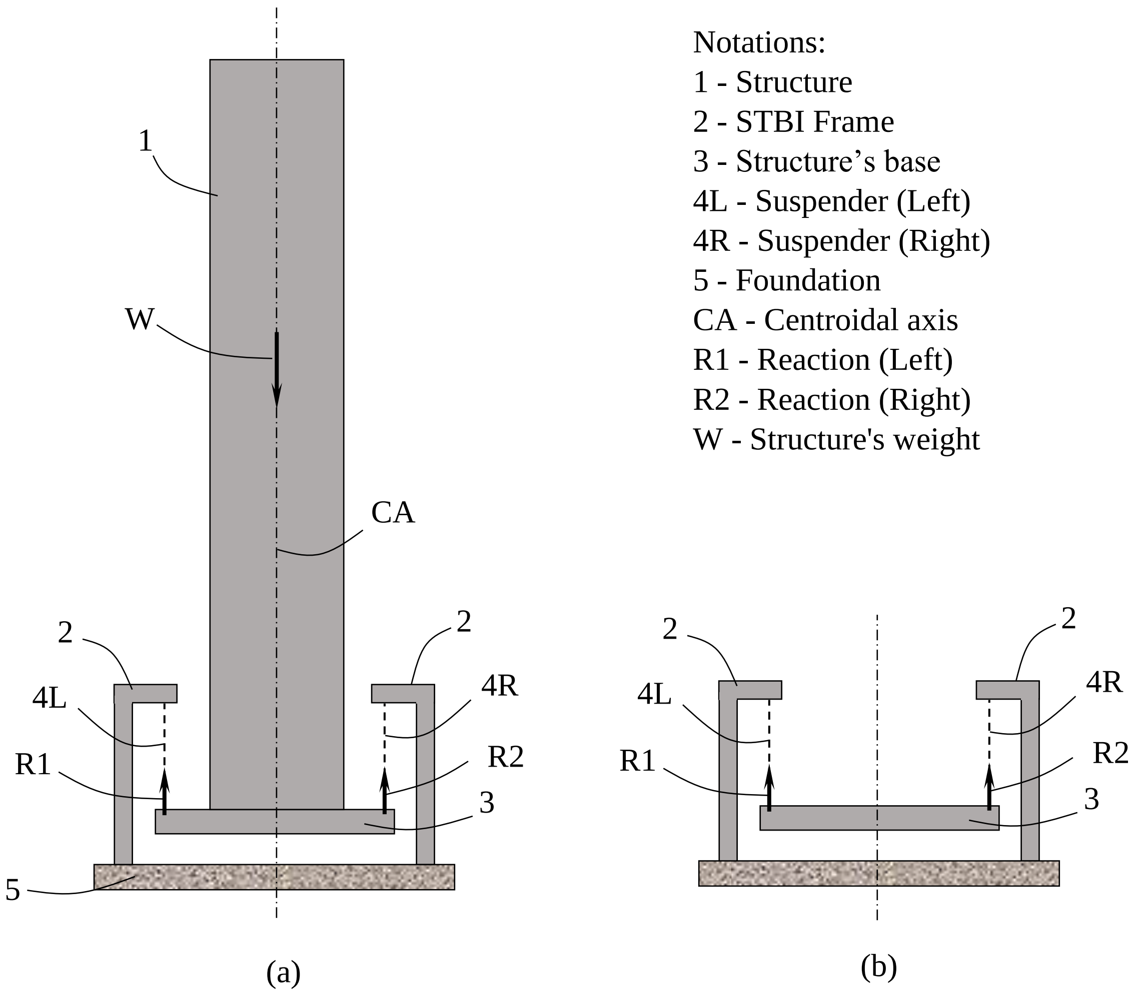


2.1.2. Not effective in auto-centering. Another limitation of the bearing type isolators is their being ineffective in auto-centering, also known as re-centering or self-centering. Auto-centering is the tendency of the building to go back to its original position after every seismic event. Figure 4 and Figure 5 show LRB and FP at deformed conditions, respectively, after seismic event. The ineffectiveness of BTI's in auto-centering may be attributed to friction between sliding surfaces [2]. The higher the coefficient of friction between sliding surfaces, the greater the resistance to building against auto-centering. Furthermore, the resistance to auto-centering would increase as the structure is becoming heavier and higher.

3. Suspension Type Base Isolation

Suspension Type Base Isolation (STBI) intends to address limitations of the bearing type isolators. It can effectively and efficiently mitigate seismic impact on structures. STBI can be implemented to all heights of structures from low-rise, mid-rise to high-rise. And being suspension type, the said isolator is effective in auto-centering.

Figure 6: Simplified Model of Structure with STBI



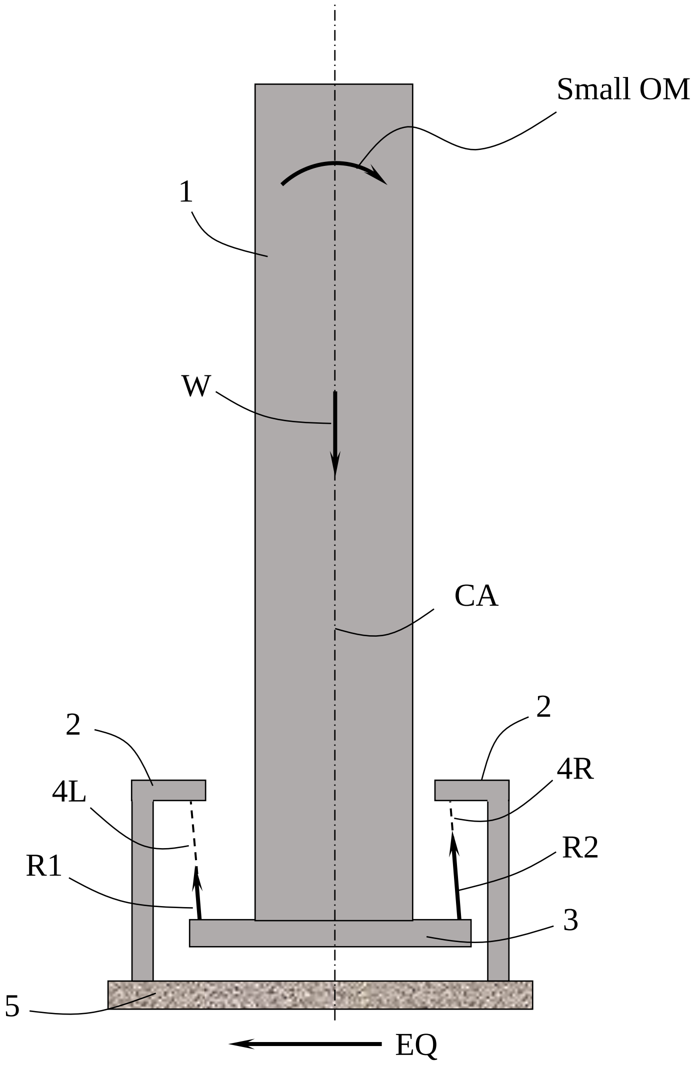
(a) (b)

3.1. Working Principle of STBI

Figure 6a shows a simplified model of structure installed with STBI. It may be noted that in this isolation system, the structure is literally suspended from the frame. Also, in the same figure, parts of the model are shown. These parts are the frame, structure's base, suspenders, and foundation. Also indicated in the said figure are the forces involved. These are R1, R2, and W, that represent reaction (left), reaction (right), and structure's weight, respectively. A vertical reference line, centroidal axis (C.A.), is drawn right at the centroid of symmetry. The STBI itself is separately shown in Figure 6b. Its parts are the frame (2), suspenders (4L and 4R), and the base (3). Foundation (5) does not belong to the isolation system. Discussion below explains various conditions under which the model structure would be subjected.

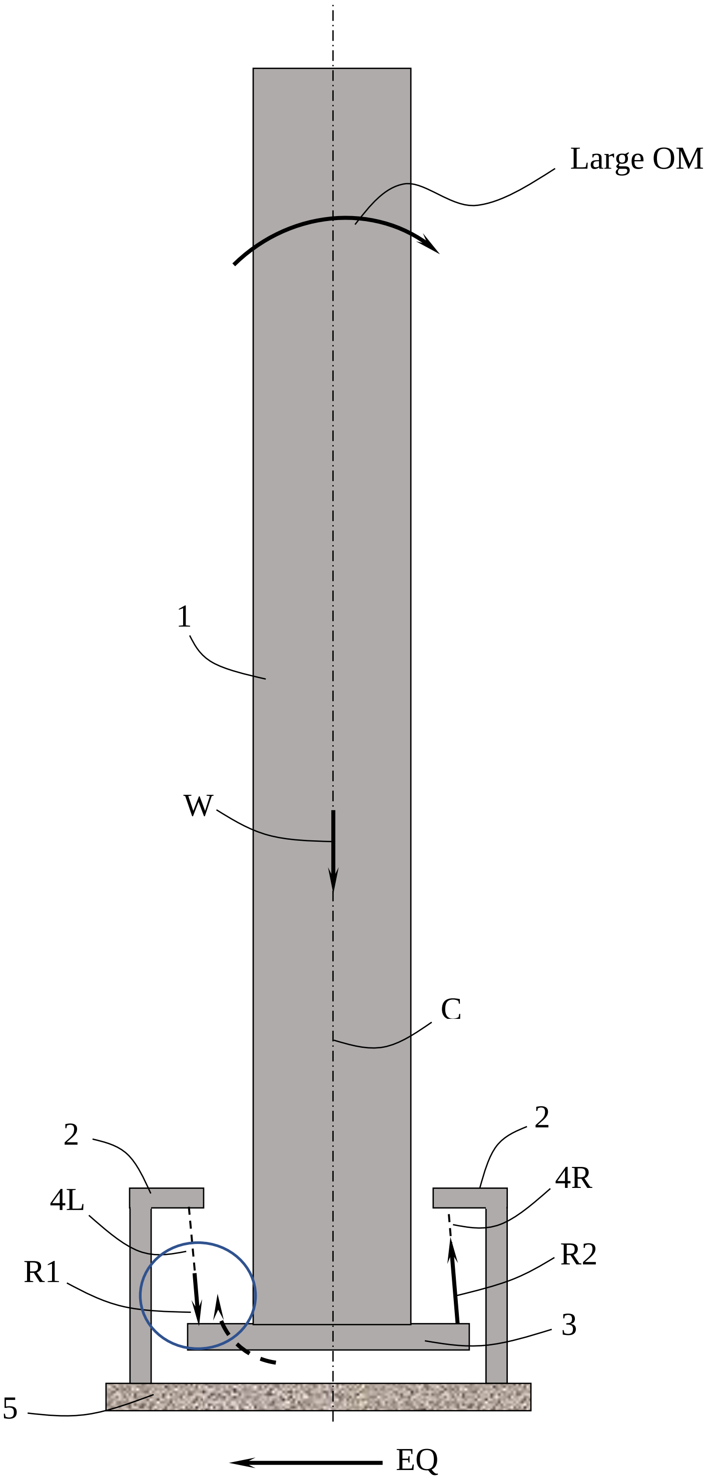
3.1.1. Condition A: No seismic shaking. At static condition (Figure 6), the model is not subjected to seismic acceleration. Forces involved in the model are weight of the structure (W), reaction at left suspender (R1) and reaction at right suspender (R2). Assuming that the structure is symmetrical about centroidal axis (CA), the reactions at left (R1) and at right (R2) are equal; and the suspenders are both under tension.

Figure 7: Model of Structure Subjected to Small OM



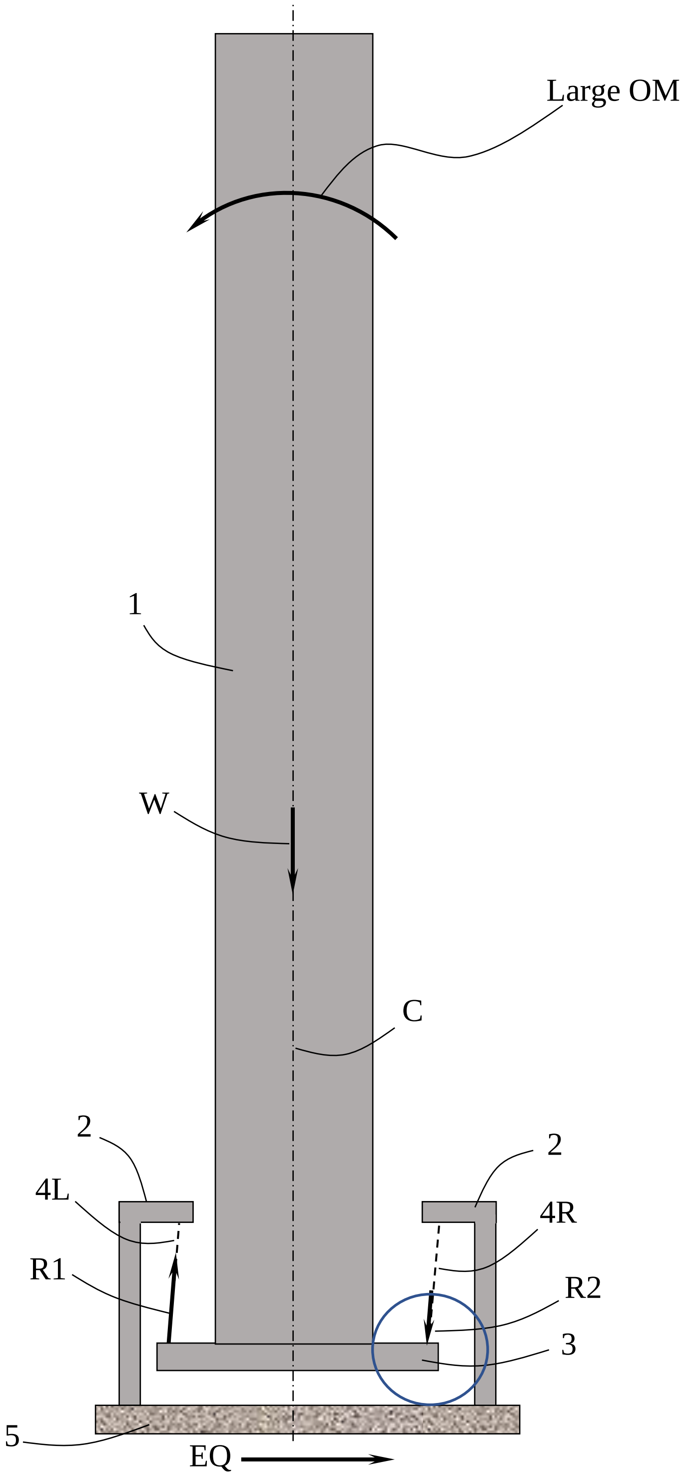
3.1.2. Condition B: With seismic shaking, small OM. This condition is possible for low-rise to medium-rise buildings and/or at weak earthquake (EQ) intensities. Under this condition, a relatively small overturning moment (OM) could be expected. Figure 7 shows that the OM is going clockwise. Although both reactions are still under tension, but reaction at the right (R2) is greater than the reaction at the left (R1).

Figure 8: Model of Structure Subjected to Large OM



3.1.3. Condition C: Strong seismic event, large OM. Relatively large overturning moment (OM) is possible if a high-rise building is subjected to strong seismic intensities, as shown in Figure 8. It will be noted that in the same figure the reaction at the right (R2) is under tension, but the reaction at the left (R1) becomes under compression. This is possible because the relatively large overturning moment (OM) can cause the base at the left to go upward. Thereby, the suspenders would be subjected to compressive forces. At this dynamic condition, bearing type isolators, like LRB and Friction Pendulum (FB), would be ineffective.

Figure 9: Model of Structure Subjected to Shaking Reversal



3.1.4. Condition D: Shaking reversal, large OM. In actual EQ events, ground shakes to-and-fro. Figure 9 shows the model of structure when seismic shaking reverses its direction. Reaction at the left (R1) becomes under tension, while the reaction at the right (R2) becomes under compression. These alternate shaking directions also subject suspenders to alternate tension and compression. Hence, the proposed suspenders must be designed and constructed to handle the said dynamic condition.

3.2. Types of Suspenders for STBI

As explained in the preceding discussions, suspenders may be under tension and compression, alternately. Hence, suspenders should be designed and constructed that can resist either tension or compression.

3.2.1. Rigid Type Suspender. Rigid type of suspender (RTS) is applicable to resist compressive and tensile forces. See Figure 10 that shows connections of RTS to frame (2) and structure's base (3). Figure 11 shows the details of RTS.

Figure 10: Model of Structure Supported by Rigid Type

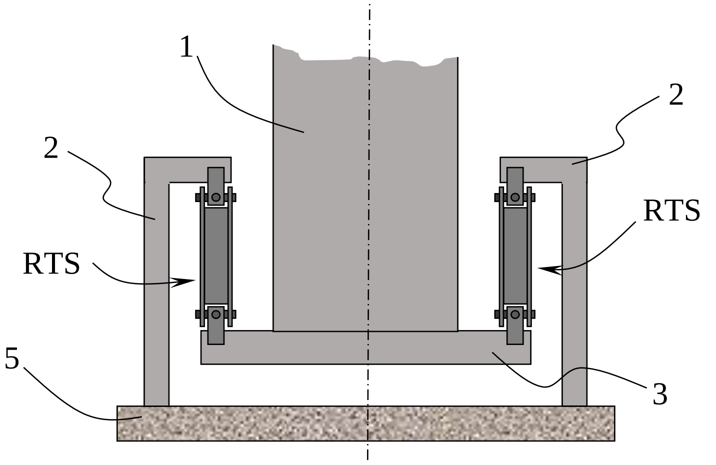


Figure 11: Details of Rigid Type Suspender (RTS)

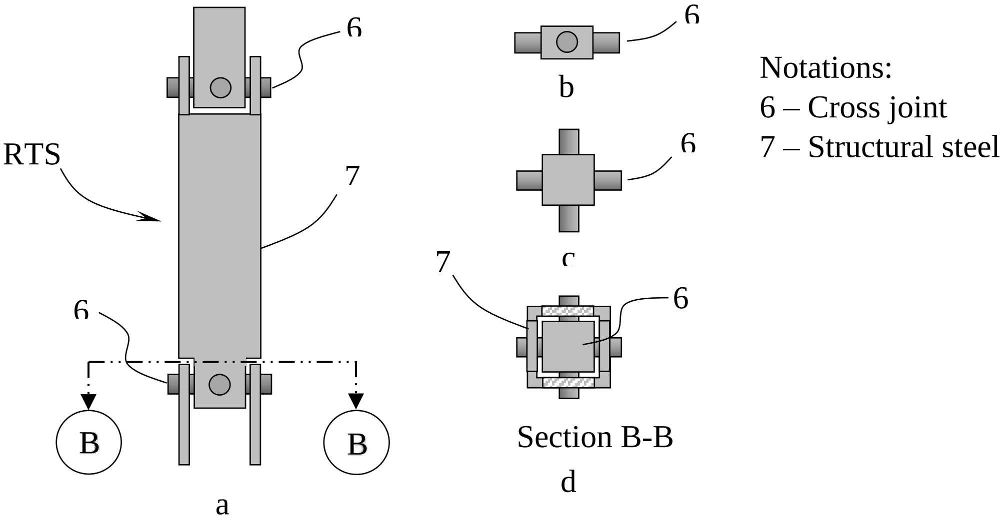
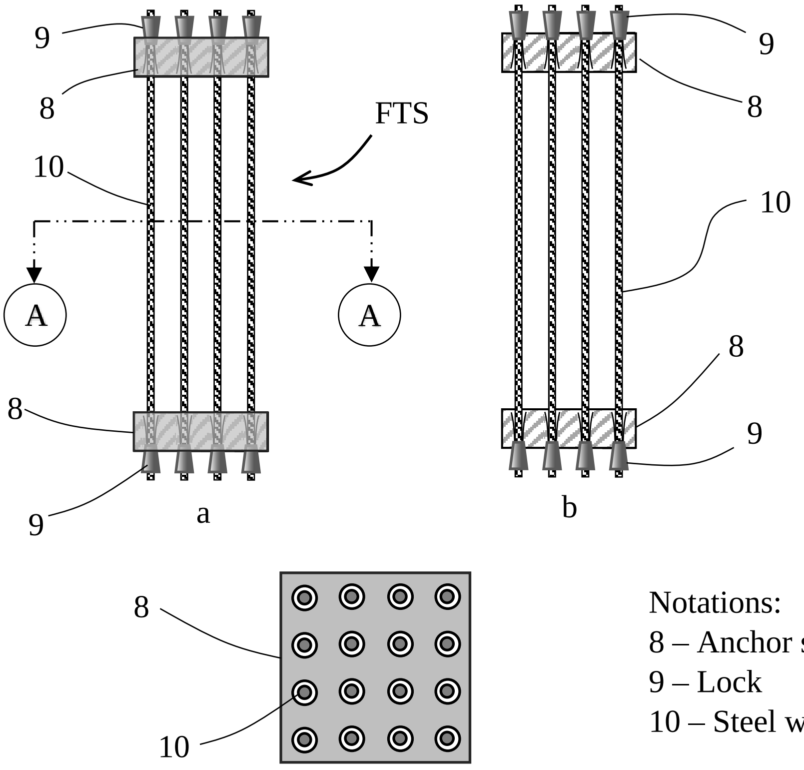


Figure 11a shows the details of RTS assembly. It is basically a construction of structural steel (7) and cross joints (6). The structural steel is known to resist compressive and tensile forces. Figure 6d shows how the structural steel is fitted to cross joint.

3.2.2. Flexible Type Suspender. In cases where suspender shall be under tension only, flexible type of suspender (FTS) is applicable. Details of the said suspender is shown in Figure 12.

Figure 12: Details of Flexible Type Suspender (FTS)



Section A-A
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Notations:
8 – Anchor steel plate
9 – Lock
10 – Steel wire cable

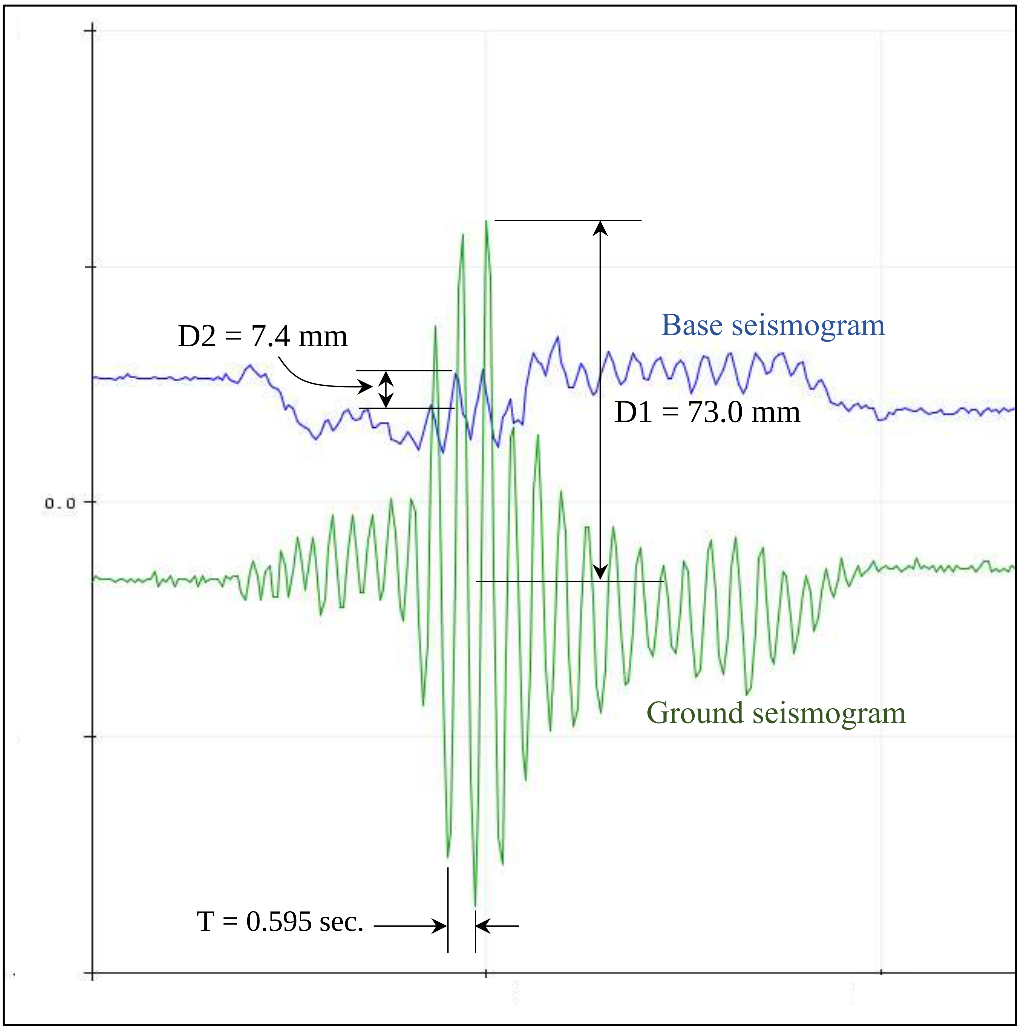
FTS is basically a construction of steel wire cable (10) [7], anchor steel plate (8), and lock (9). Steel wire cable are known for its strength as it is typically utilized in suspension bridges.

3.3. Effectiveness of STBI in Mitigating Earthquake Impact

Research conducted proves the effectiveness of STBI in mitigating earthquake impact on structure. A moment resisting frame scale model was set up in a laboratory and installed with sensors, accelerometers and strain gauges. The said scale model (similar to the one in Figure 6) was placed on a shaker especially assembled for this particular investigation. The installed sensing devices where connected to laptop through microcontroller unit (MCU) and pertinent data were collected. These data were used to determine displacements, accelerations, seismic intensities, and base shear (lateral force).

3.3.1. Reduction in displacement. Graph shown in Figure 13 presents ground (shaker) and base seismograms taken from actual laboratory test. Basing on the graph, ground (shaker) displacement (D1) and base displacement (D2) were measured. D1 is 73.0 mm while D2 is 7.4 mm. Base displacement is reduced by 65.6 mm or 89.86% relative to ground displacement.

Figure 13: Ground (Shaker) and Base



3.3.2. Reduction in acceleration. Peak ground acceleration (PGA) and base acceleration (BA) were calculated based on data (displacement and period) shown in the graph (Figure 13) and using equation (1).

$$d = \frac{1}{2}at^2 \qquad (1)$$

In equation (1), d = displacement (m), a = acceleration (m/s^2), and t = time (sec.)

Utilizing equation (1), peak ground acceleration (PGA) and base acceleration (BA) were calculated.

$$\mathrm{PGA} = \frac{2\mathrm{d}}{\mathrm{t}^2} = \frac{2(0.073)}{(0.595/4)^2} = 6.598\ (\mathrm{m/s^2})$$

$$\mathrm{BA} = \frac{2\mathrm{d}}{\mathrm{t}^2} = \frac{2(0.0074)}{(0.595/4)^2} = 0.669\ (\mathrm{m/s^2})$$

Hence, base acceleration (BA) is reduced by 5.929 m/s^2 or 89.86% relative to ground acceleration.

3.3.3 Reduction in seismic intensity. Figure 14 shows relationship between PGA and BA based on several trials performed in the laboratory. Equation (2) expresses the relationship between PGA and BA. Hence, for any value of PGA, the value of BA can be calculated.

$$\mathrm{BA} = -0.0034\mathrm{PGA}^2 + 0.0909\mathrm{PGA} + 0.1844 \qquad (2)$$

$$\mathrm{R}^2 = 0.6757$$

R^2 refers to coefficient of determination. The value of R^2 shows degree of dispersion of points from regression line on the graph (Figure 14).

Figure 14: PGA vs BA (in m/s^2)

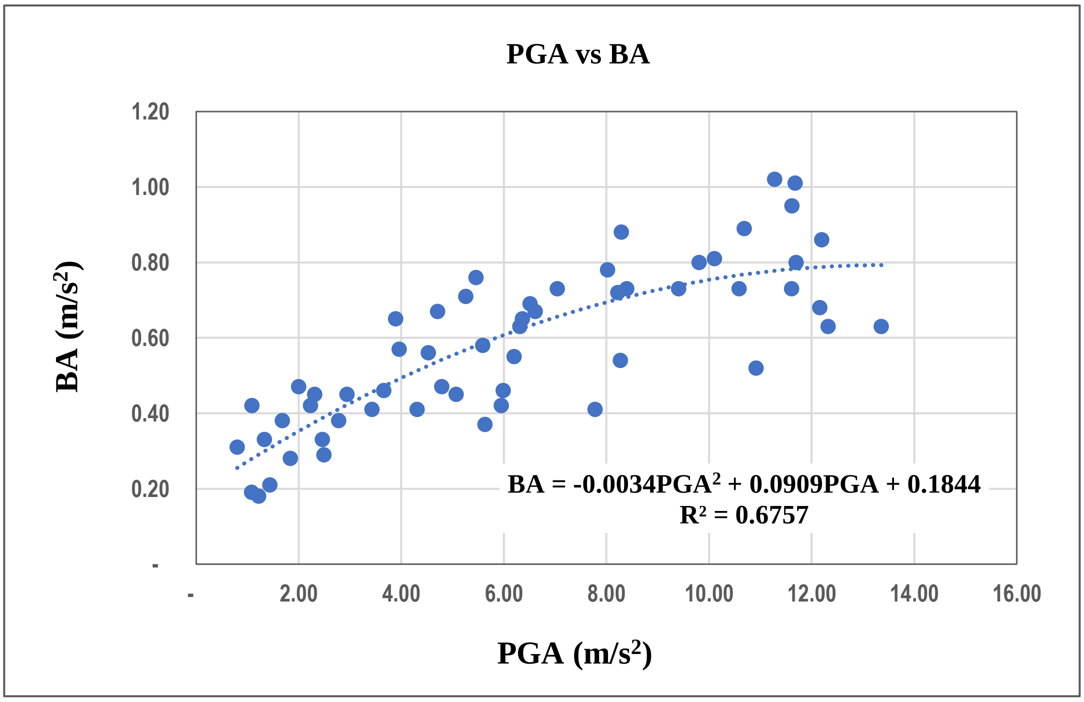


Figure 15 presents PGA and BA expressed in g (gravitational acceleration). Equation (3) shows the relationship between PGA and BA. Both are expressed in g.

$$\mathrm{BA} = -0.0333\mathrm{PGA}^2 + 0.0909\mathrm{PGA} + 0.0188 \qquad (3)$$

As an example, let us say that PGA is $1.0g$, which is intensity 9 in Modified Mercalli Intensity (MMI) scale (Figure 16). Using equation (3), BA can be determined, thus

$$\text{BA} = -0.0333(1.0^2) + 0.0909(1.0) + 0.0188$$

$$\text{BA} = 0.0764g \qquad \text{which is intensity 5 in MMI (Figure 16).}$$

Hence, simply stated, if the earthquake is intensity 9, the structure (installed with STBI) will "feel" intensity 5 only. This shows that STBI is effective in mitigating seismic impact on structures.

Figure 15: PGA vs BA (in g)

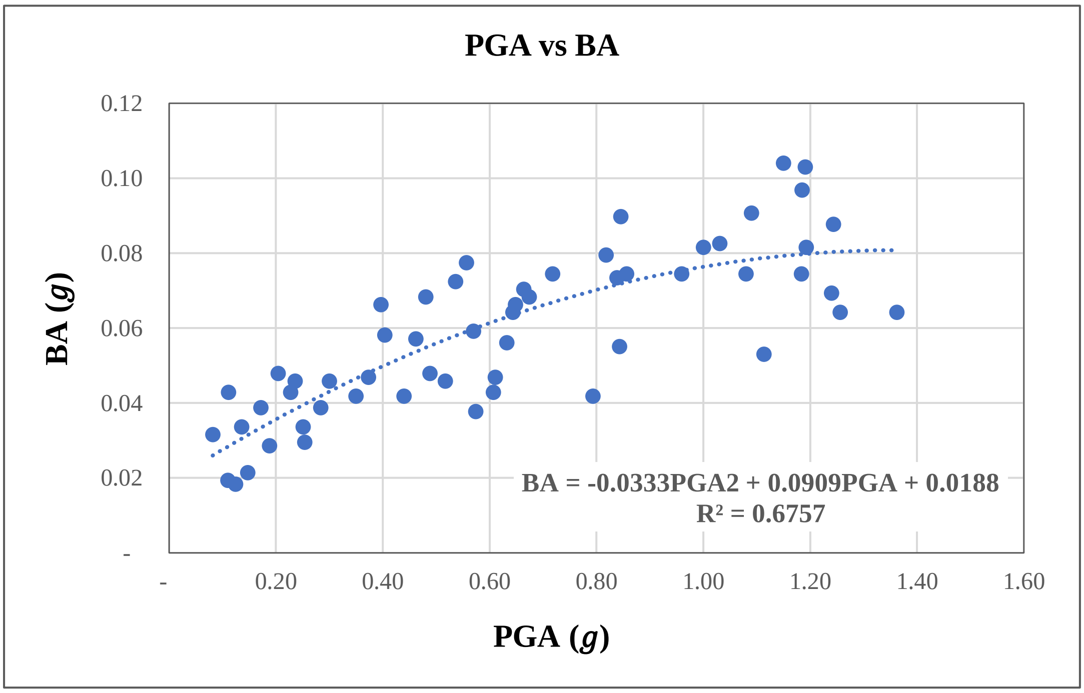
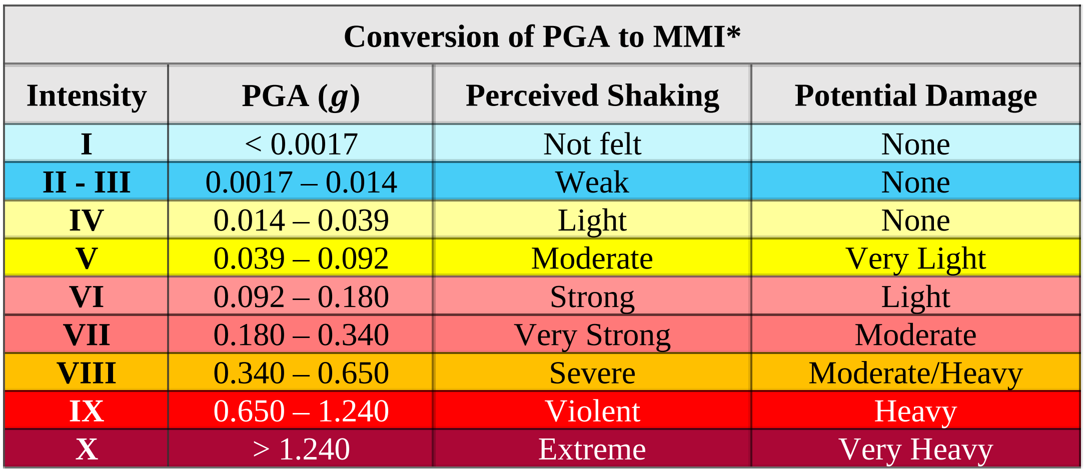


Figure 16: Conversion of PGA (g) to MMI



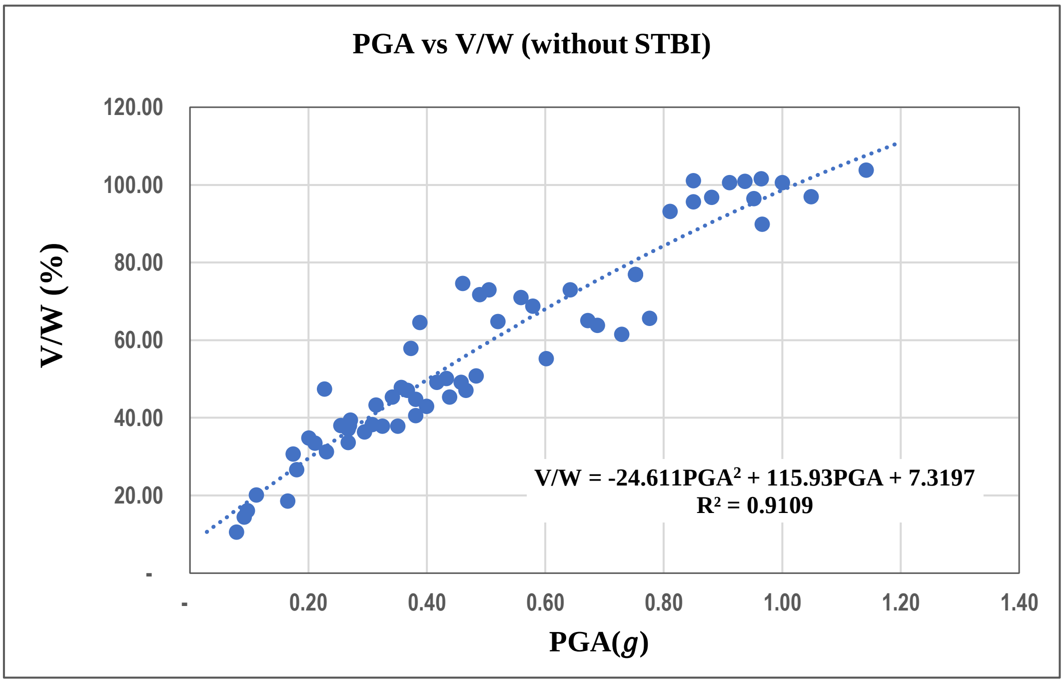
Conversion of PGA to MMI*			
Intensity	**PGA (g)**	**Perceived Shaking**	**Potential Damage**
I	< 0.0017	Not felt	None
II - III	0.0017 – 0.014	Weak	None
IV	0.014 – 0.039	Light	None
V	0.039 – 0.092	Moderate	Very Light
VI	0.092 – 0.180	Strong	Light
VII	0.180 – 0.340	Very Strong	Moderate
VIII	0.340 – 0.650	Severe	Moderate/Heavy
IX	0.650 – 1.240	Violent	Heavy
X	> 1.240	Extreme	Very Heavy

*MMI- Modified Mercalli Intensity scale

3.3.4. Reduction in base shear (lateral force). To evaluate reduction in base shear, consider two graphs shown in Figure 17 and Figure 18. Figure 17 shows the relationship between PGA and V/W in which the laboratory model does not implement STBI. On the other hand, Figure 18 shows relationship between PGA and V/W in which the model is installed with STBI. In both figures, V and W are base shear and building's total dead load, respectively. The relationship between PGA and V/W in Figure 17 is expressed by equation (4). It must be noted that STBI is not installed in the model in during the conduct of the tests.

$$(\mathrm{V/W})_{\mathrm{A}} = -24.611\mathrm{PGA}^2 + 115.93\mathrm{PGA} + 7.3197 \qquad (4)$$

Figure 17: PGA vs V/W (without STBI)



On the other hand, equation (5) expresses the relationship between PGA and V/W (Figure 18) where the model is installed with STBI.

$$(\mathrm{V/W})_{\mathrm{B}} = -0.7856\mathrm{PGA}^2 + 4.3556\mathrm{PGA} + 8.2786 \qquad (5)$$

As an example, let us consider again PGA of $1.0g$. And applying equation (4),

$$(\mathrm{V/W})_{\mathrm{A}} = -24.611(1.0)^2 + 115.93(1.0) + 7.3197$$

$$(\mathrm{V/W})_{\mathrm{A}} = 98.64\% \qquad \text{or} \qquad \mathrm{V_A} = 0.9864\mathrm{W}$$

Then, applying equation (5),

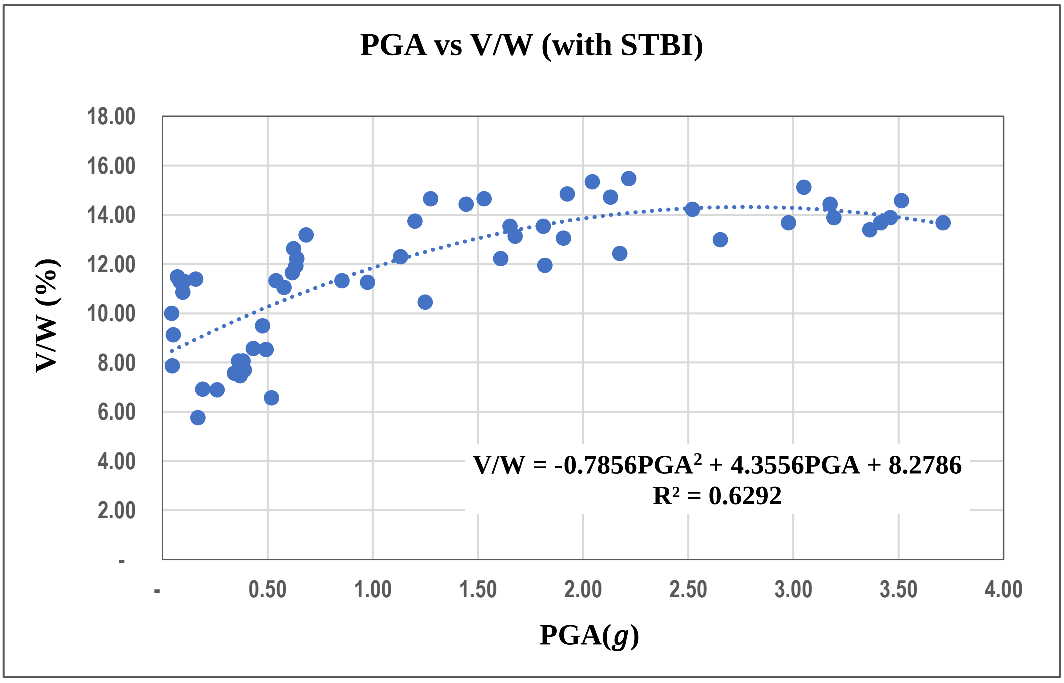
$$(V/W)_B = -0.7856(1.0)^2 + 4.3556(1.0) + 8.2786$$

$$(V/W)_B = 11.849\% \qquad \text{or} \qquad V_B = 0.1185W$$

Percent reduction in base shear ($\%R_V$) can be calculated, thus

$$\%R_V = \frac{0.9864W - 0.1185W}{0.9864W}(100) = 88\%$$

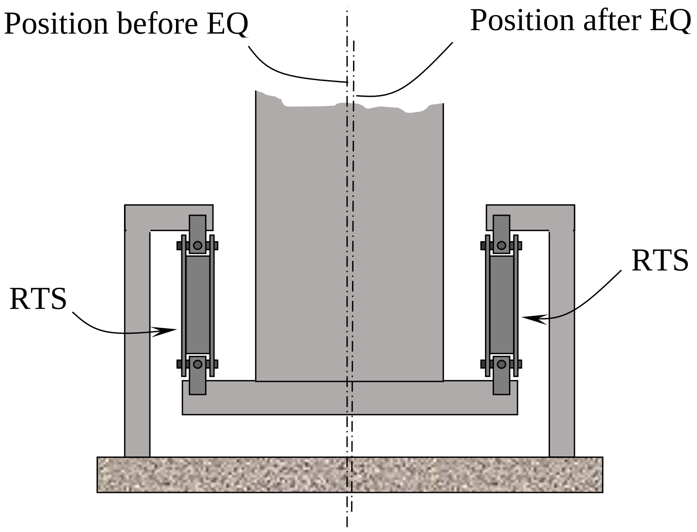
Figure 18: PGA vs V/W (with STBI)



3.4. Effectiveness of STBI in Auto-Centering

It was observed during the conduct of this study that the scale model effectively returned almost to its original position after every seismic (shaking) event. This behavior is definitely influenced by the pull of gravity. It was consistently observed during the trials that the position's discrepancy between "before" and "after" shaking was around 5 mm. This discrepancy could be attributed to friction in the cross joints. Attempting to significantly minimize friction in the cross joint is possible, but doing so is not a good idea. This is because friction in the cross joints provides some damping in the isolation system. Theoretically, if the friction would be completely eliminated, the structure would oscillate during seismic events. And this would provide sustained stresses on structure.

Figure 19: Model of Structure Before and After Seismic Event



4. Conclusion

Research conducted on a prototype model of moment-resisting frame shows that Suspension Type Base Isolation is very effective and efficient in mitigating earthquake impact. This isolator can be installed in all types of structures from low-rise, mid-rise, to high-rise. Structures installed with STBI would “feel” earthquake intensity 5 only, although the actual ground shaking could be intensity 9. This results to earthquake impact mitigation. Test showed that base shear (lateral force) reduction can be around 88% compared to non-isolated structure. The said STBI is also effective in auto-centering, that is, the building would tend to sway back to original position after seismic events. Another advantage of its implementation to proposed structures is that the proposed project could be cost-effective because reduction in base shear could be translated to reduced structural members. Hence, this would result to reduction in materials used in construction of the structure. The cost of fabricating STBI could also be cost-effective compared to LRB and FP. Materials for STBI can be easily sourced and its fabrication can be done in-house using readily available machine shop equipment.

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