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A NEW GENERATION OF HIGH DAMPING NATURAL RUBBER BEARINGS: MATERIAL DEVELOPMENT, TESTING AND APPLICATIONS

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Abstract

This paper reports on the research and development activities carried out for the development of a new material, based on natural rubber, specially formulated to give a hysteresis damping of minimum 22% at design shear strain. The use of the high damping rubber compound developed avoids the need for lead plug to be inserted in the bearing and the need for auxiliary dampers such as viscous or elasto-plastic steel dampers in the isolation system. Material development and experimental activities, including qualification tests on full scale isolators, are presented. The influence of such factors as temperature, aging and horizontal deformation amplitude upon the stiffness and damping are discussed. Evidence for the long term stability of the properties of the newly designed bearings is given. The paper also gives examples of the application of the innovative super high damping rubber bearing (S-HDRB) to base isolation in Indonesia by referring in particular to application to health care facility and commercial tower projects recently completed in high seismicity areas.

Keywords: high damping rubber bearing; seismic isolation; hysteresis damping; hospital; office tower

1. Introduction

Seismic isolation has been actively used in earthquake prone countries over the past few decades after it has been proven to effectively reduce the damage of severe earthquake on structure. For instance, the use of base isolation in Japan has increased tremendously to over 150 buildings a year after the 1995 Kobe earthquake [1]. Past earthquakes have raised certain doubts among engineers about the ability of conventional seismic design concept in protecting structures and their contents.

Hence, instead of strengthening the critical structural elements to resist lateral load from ground motion or providing intended plastic hinge location to dissipate energy, the concept of base isolation actually decouples the building from ground movement. This is achieved by providing an interface with relatively lower lateral stiffness between the structure and the foundation. This prolongs the fundamental natural period of the structure (Fig. 1). Sometimes, the isolation level can vary depending on several other factors.

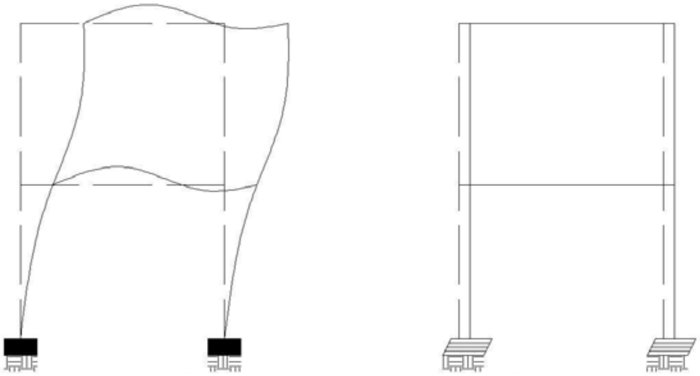

Fig.1 Response of fixed-base and seismic isolated structure due to lateral loading

Originally, occurrence of some hysteresis damping in isolation device is beneficial to avoid the resonance effect. Nevertheless, the introduction of lead rubber bearing (LRB) in the 80s' has pushed the demand of hysteresis damping to a higher level. This led to the invention of numerous energy dissipating devices that are installed at the isolation level to increase the damping of other isolation systems, particularly natural rubber bearing (NRB). Natural rubber does not possess higher hysteresis damping in shear. Breakthrough in the material research of rubber has successfully increased the damping of modified rubber compound from 2 to 3% previously to 6 to 8%. EN 15129 [2] has classified isolation system with hysteresis damping below 6% to be deemed as low damping device. In other words, high damping rubber bearing (HDRB) refers to seismic isolator which possesses hysteresis damping above 6%. Such base isolation system has been rather well-established and one of its remarkable applications is the seismic isolation of Second Penang Bridge in Malaysia. This is the longest structure in the world to be mounted on more than 2000 pieces of high damping rubber bearing [3].

2. Problem Background

In one of a recent hospital construction projects in the capital of Indonesia - an earthquake prone countries, the shortlisted manufacturer has proposed the sole usage of HDRB system to the structural designers and consultants. Initial design requirements from the Japanese structural consultants comprised combination of few other systems including lead rubber bearing and high damping rubber bearing with additional energy dissipating devices to increase the damping of isolation interface. The structural designers partially agreed to the proposal on condition that all the HDRD must possess hysteresis damping above 20% without any additional damping devices. If this were achievable, the cost of seismic isolation for the project would reduce tremendously. In addition, this also eliminated the need of complicated connection between different devices.

Doshin Rubber Products (M) Sdn. Bhd. investigated the possibility of increasing hysteresis damping of natural rubber by altering the chemical composition during mixing process. The work was carried out in collaboration with Malaysia's counterpart of Rubber Research Institute (RRI) in London - the Tun Abdul Razak Research Center (TARRC). By changing the formulation in rubber mixing process, the material testing performed in the laboratory of TARRC has witnessed higher possibility of increasing the shear hysteresis damping of rubber compound beyond 20% at 100% shear strain. While the material sample testing was able to be performed in TARRC, testing the full-scale of HDRB using the new rubber compound would require large testing facility. This needed to be done before the structural consultants would consider the proposal of using solely HDRB to meet the high damping requirement.

One of the reasons for the need of higher damping in the isolation system for the hospital project is because of the displacement demand. The green-themed 13 story building would be the first seismic isolated hospital in Indonesia, housing expensive and vibration sensitive equipments including a satellite clinic. At 70m tall, the completed building has a total built area of approximately 100,000 m^2. Plan layout of the building is shown in Fig. 2. The structural consultants from Japan have designed the building to withstand earthquake up to 6 on the Shindo scale. Sources from the structural designers indicated that the hospital was designed with seismic design parameters, S_S and S_1 of 0.3 and 0.15g respectively for a return period of 500 years. Meanwhile, the 2500 year return period parameters were 0.6 and 0.25g respectively. At such earthquake magnitude, the ground shake intensity could be devastating for most civil engineering structures. Since the base isolation works by prolonging the fundamental period of the structure, the decrease in acceleration response is compensated by having larger displacement via the isolator. Hence, damping is additionally required to decrease the displacement demand of the isolation system.

3. Super High Damping Rubber Bearing (S-HDRB)

The finalized structural design requirement from the consultants required minimum damping ratio of 24% of S-HDRB compared to the typical HDRB which possess hysteresis damping around 8 to 12% at design shear strain. The higher damping was required to reduce the design displacement of the isolation system due to two main key factors: (i) the high ground acceleration used in design and (ii) the building sits on soft soil which further amplifies the seismic waves from bedrock.

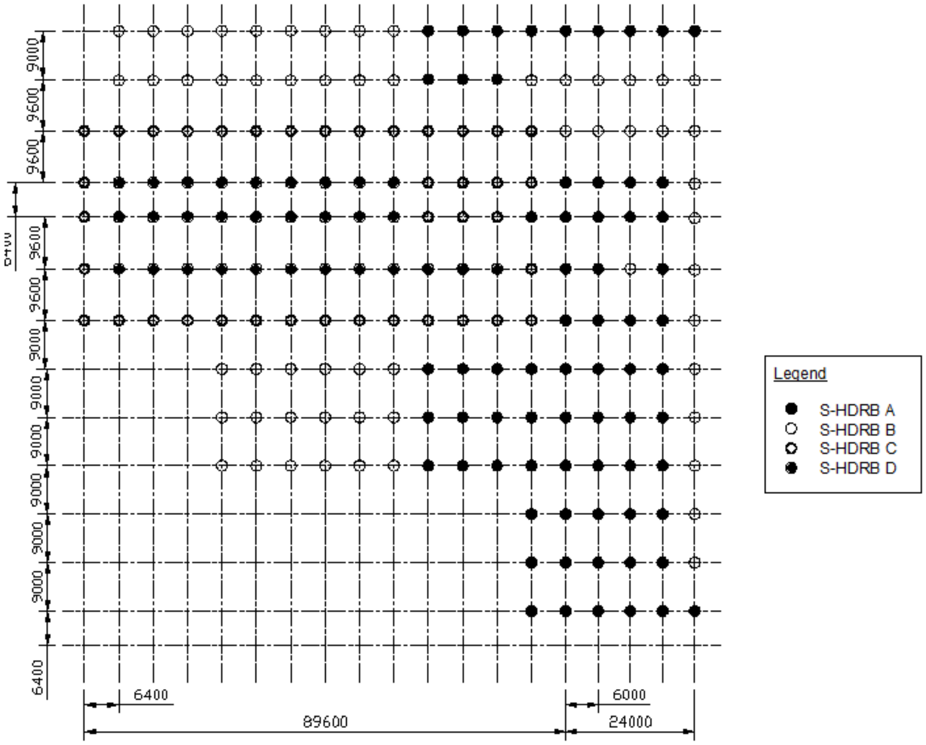

Fig.2 Plan view showing the location and types of isolator used for the hospital project

The base isolation was designed to provide a composite natural period around 3s. The damping ratio of 0.24 was needed to reduce the design displacement to 200mm. Otherwise; additional damping devices were required at the isolation layer to achieve such displacement reduction. Based on the loadings of each vertical supporting member, four groups of S-HDRB were proposed (see Table 1).

Table 1 – Design properties of S-HDRB

Parameters	**Unit**	**S-HDRB A**	**S-HDRB B**	**S-HDRB C**	**S-HDRB D**
Diameter	mm	800	1100	1200	1300
Shear modulus	MPa	0.620	0.620	0.620	0.620
Total rubber thickness	mm	200	200	200	200
Inner diameter	mm	20	55	55	55
Height	mm	422.2	390.2	385.6	376.9
Effective shear stiffness	kN/m	1560	2940	3500	4110
Damping ratio	%	24	24	24	24

Material properties of the modified rubber compound (such as aging and dependency on surrounding temperature) were investigated in TARRC before mass production of the seismic isolators began. A complete guide of material tests can be found in EN15129 [2] which states clearly which ISO standard is used for each specific testing. For instance, the accelerated aging was carried out at 70^{0}C inside an air oven for 14 days. The accelerated aging test was performed in anaerobic condition by wrapping the test specimen with three impermeable rubber compounds. The aging process has increased that shear modulus by 12% while the damping ratio decreased around 5%. This satisfies the EU Standards that imposes a maximum limit of 20%. Meanwhile, temperature test ranged from 19 to 45^{0}C imposed changes in shear modulus and damping ratio around 10%.

3.1 Bi-axial shear test

Since the structural designers are engineers from Japan, the actual testing procedures are based on Japanese Industrial Standards [4]. The manufacturer has proposed for the test to be carried out according to the European Standards, namely EN15129 (CEN, 2007) to which the consultants agreed. After all, there are a lot of similarities between the two codes particularly when it comes to defining important testing parameters such as calculation of damping ratio, and loading procedures.

Prototype testing of the full-scale S-HDRB requires extensive modal investment in the test facility to accommodate the large force as well as displacement amplitude. Doshin Rubber has invested heavily on such facilities. Apart from the usual laboratory equipment for material testing, the bi-axial test of the S-HDRB for this project will be performed by eLab-140 (see Fig. 3). This machine has the ultimate compression capacity of 20,000kN and is able to shear up to 2,000kN with full-cycle of ±500mm. It can accommodate test specimen up to 1m in diameter. In addition to eLab-140, a relatively newer machine was just recently added to the large collection of testing facilities, namely the eLab-150 (see Fig. 4). It is used to test isolator with diameter up to 2m. With the capacity of ±1000mm, the machine is able to generate compressive force of 50,000kN and shear up to 5,000kN. The bi-axial test was carried out in single-shear configuration (which is preferred by EN15129) instead of the common double-shear arrangement. In practice, single-shear setup is far more complex because it involves the moving mechanism of the test rig itself. In a double-shear configuration, the horizontal actuator provides push-and-pull forces at the connection between the two isolators. However, the test results need to be averaged since it involves two pieces of specimen in a single test.

Fig.3 eLab-140 testing machine

Fig.4 eLab-150 testing machine – one of the world's largest

Fig. 5 shows the bi-axial test of S-HDRB A in a single-shear configuration. The isolator was loaded with constant nominal compressive force in the vertical direction which reflected the weight from column supported by the isolator in reality. While the compressive force was locked in position, the horizontal actuator slid the base of the isolator in the horizontal direction at 0.33 Hz which corresponded to the design period of 3.0s. Three full-cyclical shear tests at ±200mm (100% design shear strain) were performed to obtain the hysteresis loops of the isolator (see Fig. 6). Effective shear stiffness and damping ratio were reported based on the 3rd cycle of each test.

Fig.5 Dynamic shear test of S-HDRB A under repetitive full-cyclical loading

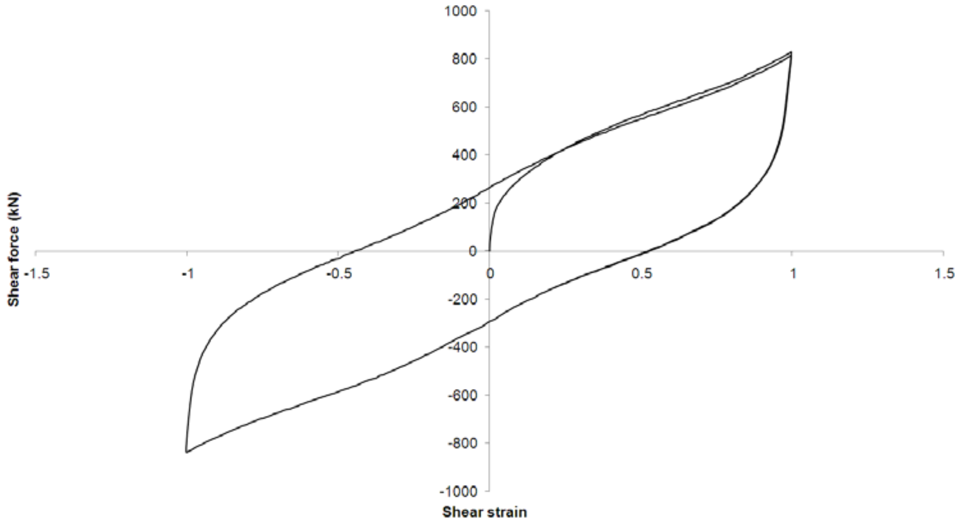

Fig.6 Hysteresis plots of S-HDRB A in terms of shear force versus shear strain

3.2 Quality control test

Quality control test requires the exact tests as described previously (in section 3.1) to be repeated to all the S-HDRB manufactured before shipment. The main reason for such demand is that the structural designers needed to be affirmed that the newly-modified rubber compound had adequate consistency. Shear stiffness and damping values were reported from the 3rd cycle of each hysteresis loops. It was clearly specified by that the maximum difference between laboratory obtained results and designed values must not exceed 20%. Percentages of difference between the parameters are plotted in Fig.7 and it was clearly revealed that all the rubber bearings performed rather well within 10% of accuracy, way better than expected.

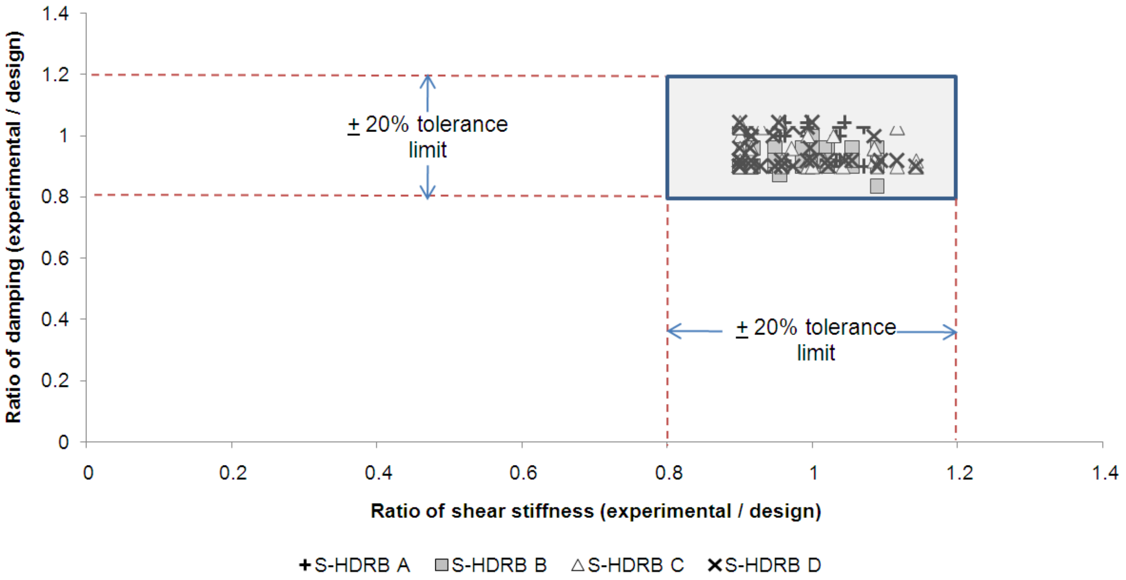

Fig.7 Consistency of shear stiffness and damping ratio of 100% product testing within 10% accuracy

3.3 Ultimate displacement test

This section describes the additional test that was required by the consultants from Japan, which was normally not specified in the codes for most base isolation projects. First, is to demonstrate that all the rubber bearings are able to undergo shear displacement above 300% strain and most obviously, without being damaged. Above 300% shear strain, the rubber bearing is allowed to break on condition that all the 10 samples must show good consistency at their breaking strain. It is almost impossible to break a full-scale 800mm diameter bearing. The sudden release of breaking force will mostly damage the mechanical counterpart of the test rig. Hence, S-HDRB A was chosen to be scaled-down by half the original dimension (see Table 2).

Table 2 – Detail of scaled-down S-HDRB A2 for the large displacement shear test

Parameter	**Unit**	**S-HDRB A2**
Effective Outer Diameter	mm	400
Shear Modulus	MPa	0.385
Thickness of one rubber layer	mm	2.7
Number of rubber layers	Nos.	37
Total rubber thickness	mm	100
Inner diameter (hole)	mm	90
Height	mm	210
Compressive stress	MPa	12

Natural rubber with low damping behaves rather linearly, at least within the design shear strain. Nevertheless, high damping rubber tends to become stiffer at two specific displacement regions. At lower shear strain, say, 20% of design shear strain, the shear modulus of the high damping rubber compound is way stiffer than its designated value. This initial stiffness is usually where the additional damping comes from. At larger displacement (usually under MCE), for instance above 2.5 times design shear strain, rubber exhibits significant stiffening due to the strain-induced material crystallization (see Fig. 8). The figure clearly shows a significant increase in shear stiffness beyond the second red-dotted line. This may be beneficial to control excessive displacement demand under extremely rare but stronger earthquake. From the structural analysis report by the structural consultants, the displacement at MCE would be 2.5 times the design shear strain. This is still within the controlled-stiffness region of the rubber bearing. Report on comparison of rubber stiffening at large displacement between HDRB and S-HDRB can be found in Tiong *et al.* [5]. Fig. 9 shows the results of breaking test. All 10 samples of S-HDRB A2 failed in shear at approximately 325% shear strain (shown by the dotted line in the figure) at which the shear stiffness reduced rapidly.

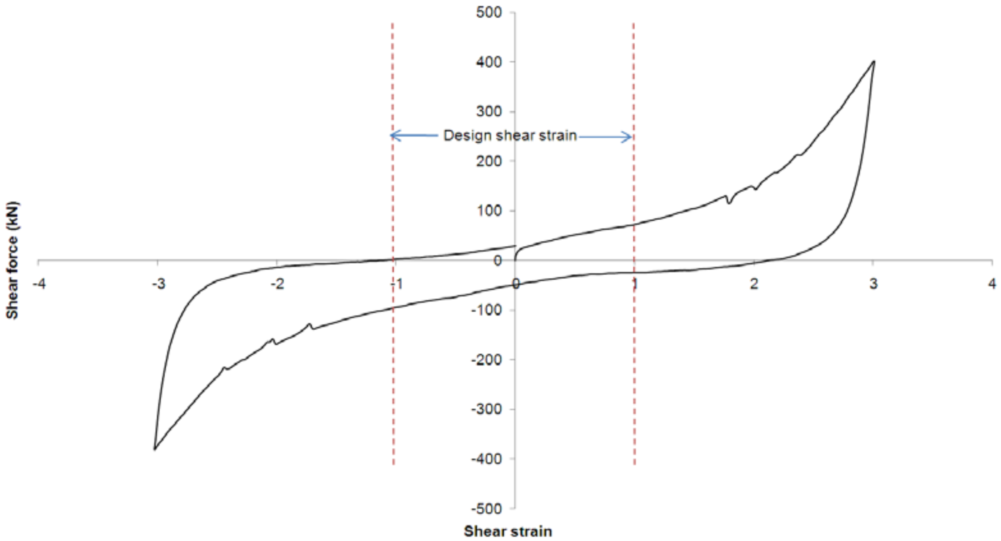

Fig. 8 Hysteresis plots of S-HDRB A2 subject to 300% shear deformation

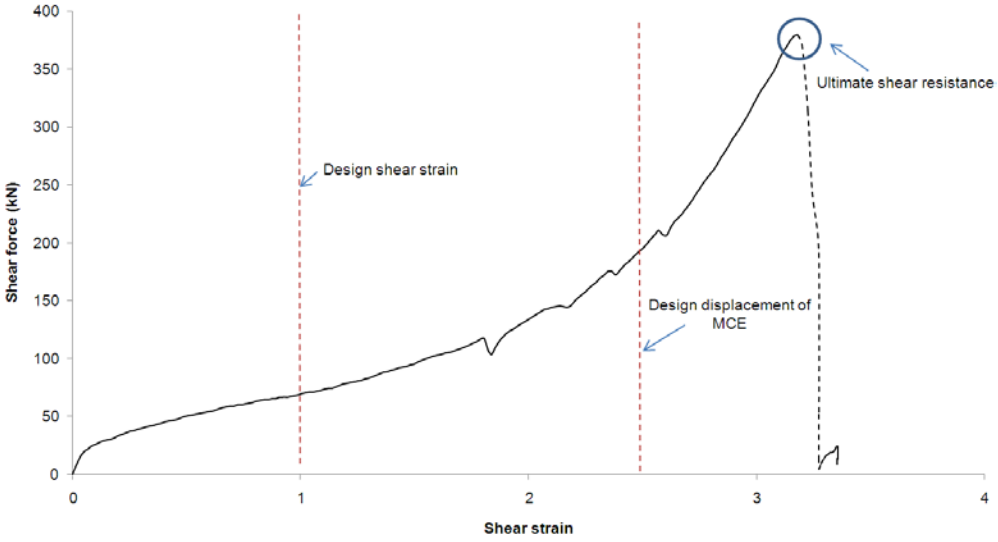

Fig. 9 Ultimate shear resistance of one of the test samples of S-HDRB A2

4. Application of S-HDRB

The first application of S-HDRB was in a hospital in Jakarta, Indonesia as described in earlier section within this paper. It is the first green-themed hospital in the earthquake prone country to be mounted on seismic isolators using this high damping technology. Besides the quality assurance warranted by the manufacturer, Doshin Rubber has also successfully supplied all the two hundreds over bearing to the construction site in less than 2 months time after the prototype witness test was approved by the designers. Fig. 10 shows the installation of all the rubber bearings at the construction site. In the very same year, an office tower in Jakarta also applied the same rubber bearing products to isolate the structure. According to the owner, leasing of the amenities was completed way before the completion of the project due to the extra seismic protection provided via base isolation. Installation of the rubber bearing at the office tower is shown in Fig. 11. One of the S-HDRB is openly exhibited to attract visitors to the building.

Fig. 10 Installation of S-HDRB at construction site of a hospital in Jakarta, Indonesia

Fig. 11 Installation of S-HDRB at office tower and exhibition of the isolator to visitors

5. Conclusion

This paper presents a newly modified natural rubber compound that was used to produce seismic isolator that possessed hysteresis damping ratio above 24%, which the authors named it super high damping rubber bearing (S-HDRB). As a general rule of thumb, higher damping is required at isolation interface to reduce large displacement demand in some (although not all) types of ground motion. Specific tests of the rubber material were presented and the final product of S-HDRB itself was also tested according to EN15129. It was found that the modified rubber compound exhibited satisfactory performance in all the conditions set by the manufacturing codes. Hence, this technology has been applied in two recent projects in Jakarta where seismic incidents are frequent. One of the buildings is the first green-themed hospital structure in Indonesia to be seismic isolated while the other project is the first office tower in the same province to use the same seismic mitigation technology.

6. Acknowledgment

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7. References

[1] Nakashima M, Pan P, Zamfirescu D, Weitzmann R (2004): Post-Kobe approach for design and construction of base-isolated buildings. *Journal of Japan Association for Earthquake Engineering*, **4**(3), 259-264.

[2] CEN (2007): *EN 15129 - Anti seismic devices.* British Standards Institutions.

[3] Malek KA, Ahmadi H, Muhr A, Stephens I, Gough J, Picken J, Lee JJ, Zulkefli MU (2013): Seismic protection of 2nd Penang crossing using high damping natural rubber isolators. *Associazione Nazionale Italiana Di Ingegneria Sismica.* Padova, Italy.

[4] JSA (2011): *JIS K6510-1 - Elastomeric seismic-protection isolators for buildings. Part 1: Specifications.* Japanese Standards Association.

[5] Tiong PLY, Or TT, Dusi A (2016): Performance of super high damping rubber bearing at large displacement using modified rubber compound. *2016 World Congress on Advances in Civil, Environmental, and Materials Research*, Jeju, Korea.