

ELASTOMERIC SEISMIC-PROTECTION ISOLATORS FOR BUILDINGS AND BRIDGES

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Abstract A giant earthquake of magnitude 9.0 occurred in Pacific Ocean off of Tohoku District Japan on March 11, 2011. The highest seismic intensity of 7 in JMA scale was recorded in Miyagi. In the Tohoku district, around 230 buildings are seismically isolated (hereafter, SI) mainly by elastomeric isolators (seismic rubber bearings). According to the official survey reports by several organizations (for example^[1]), the records of those buildings have verified the effectiveness of the seismic isolation. The response acceleration of the SI buildings was reduced by 30% to 50% of the input ground acceleration. Additionally, the difference of the conditions inside the room between SI and the fixed-base buildings was obvious as well as the damage in main structures of the buildings. The displacements of the isolators by the earthquake were around 200 mm according to the records of the instruments. As a result, the performance of SI buildings and the elastomeric isolators in the Tohoku District — Off the Pacific Ocean Earthquake 2011 were excellent, and the efficiency of the seismic isolation was verified by the records of many buildings in wide area.

Keywords: Elastomeric isolator; Seismic isolation; Rubber bearing.

INTRODUCTION

Seismic isolation is an aseismic design concept to reduce the seismic force transmitted to the structure by supporting with a flexible element — elastomeric isolators — at the base or sometimes middle story of the buildings, to elongate the natural period of the structure and thereby decouple it from the ground (Fig. 1). Basically, seismic isolation systems provide functions of restoring force and energy dissipation. Seismic isolation has gained popularity in the recent decade as a counter measure of seismic protection of structures. This is especially true in Japan, where over 2600 SI (hereafter, SI) buildings have been constructed or are under construction. Figure 2 shows the growth of the number of SI buildings in Japan. It is obviously observed that the number has drastically increased after 1995 Hyogoken Nambu (Kobe) earthquake. Since 1995, there occurred 7 major earthquakes, whose moment magnitude was more than 6.0, in Japan until the 2011 Tohoku-district off the Pacific Ocean Earthquake. The seismic isolation technology has been applied to many types of buildings as shown in Fig. 3. Apartment has the largest number of application, followed by office buildings and hospitals. In these earthquakes, SI buildings verified its effectiveness by its performance during earthquakes.

ELASTOMERIC ISOLATORS

The elastomeric isolator, made up with layers of alternating rubber and steel plates, as shown in Fig. 4, is the most popular device for providing restoring force. The two components of the elastomeric isolators, rubber and

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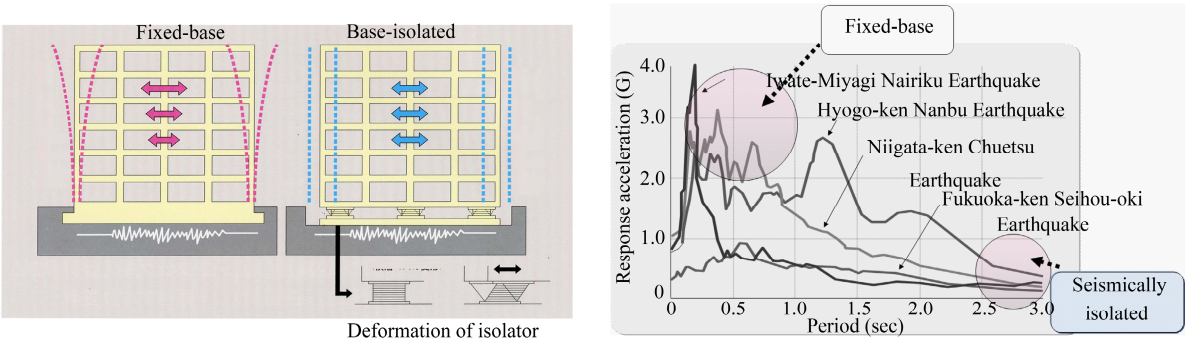


Fig. 1 Principle of seismic isolation

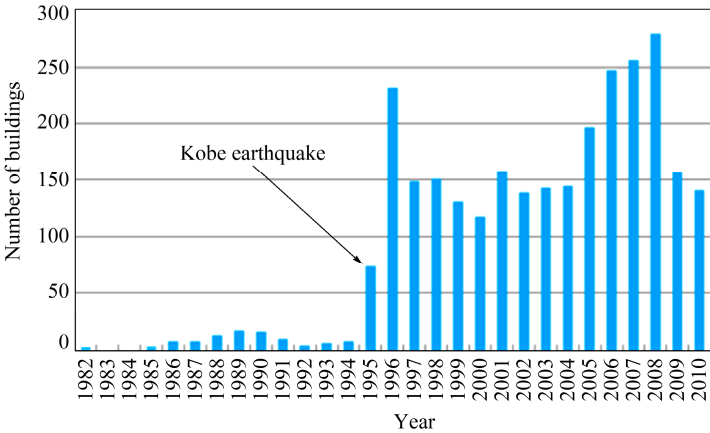


Fig. 2 Growth of the number of SI buildings (courtesy of the Japan Society of Seismic Isolation)

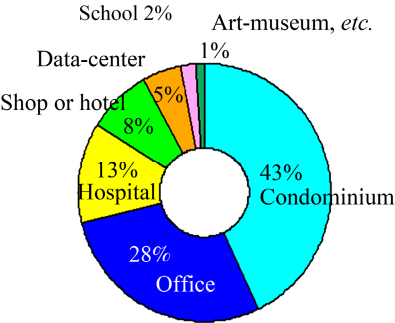


Fig. 3 Various application of seismic isolation

steel plates, are bonded to each other by strong adhesion materials. The function of the steel plates is confinement of the rubber layers to support vertical loads with low horizontal stiffness. Generally, the ratio of the vertical and horizontal stiffness is over 1000, as shown in Fig. 5. There are three types of elastomeric isolators. They are Natural Rubber Bearings (NRB), High-damping Rubber Bearings (HDR), and Lead-core Rubber Bearings (LRB). The NRB has almost linear characteristics in the horizontal force-displacement relationship, and its damping is low, such as 2% to 4% in equivalent damping ratio. Therefore, when using NRB, additional damping devices such as hydraulic dampers, steel bar dampers or friction dampers, are required for energy dissipation. HDR is a type of rubber bearing in which a specially-compounded rubber material is used to provide energy-dissipation capability during deformation, in addition to its restoring function with its stiffness

(Fig. 6). Tables 1 and 2 show typical examples of compound configuration and physical properties of HDR compounds respectively. LRB is another type of rubber bearing that has both spring and damping functions combined. The cylindrically shaped lead core is vertically inserted at the center of the bearing for energy dissipation.

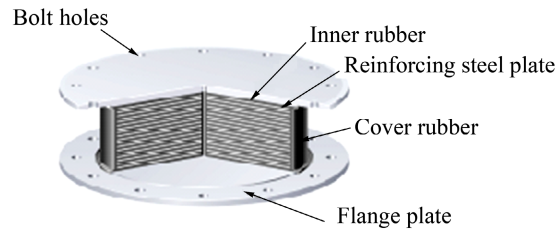


Fig. 4 Basic construction of elastomeric isolators

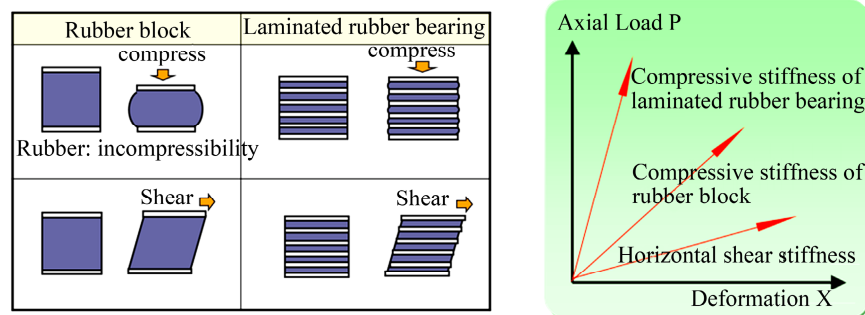


Fig. 5 Principle of laminated rubber bearings

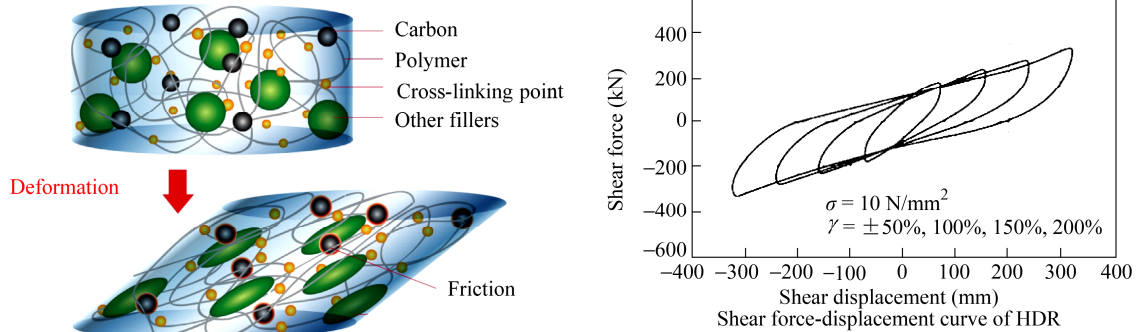


Fig. 6 Mechanism of energy dissipation in high-damping rubber bearings

Table 1. An example of compound configuration of HDR (weight ratio, %)

	Natural rubber Synthetic rubber	Filler (Carbon <i>etc.</i>)	Sulfur <i>etc.</i>
Inner rubber	> 35	> 25	< 40
Cover rubber	> 40	> 15	> 40

Table 2. An example of physical properties of HDR compound

Properties	Standard	Characteristics	
Hardness	JIS K 6253	53 ± 5	
100% modulus	JIS K 6251	0.73 ± 0.2	N/mm ²
Tensile strength	JIK K 6251	≥ 8.5	N/mm ²
Elongation at break	JIK K 6251	≥ 780	%

Testing of isolators is generally conducted with a compression-shear testing machine. Figure 7 shows a typical testing machine for isolators, and Fig. 8 shows typical parameters determined by the compression-shear testing machine.

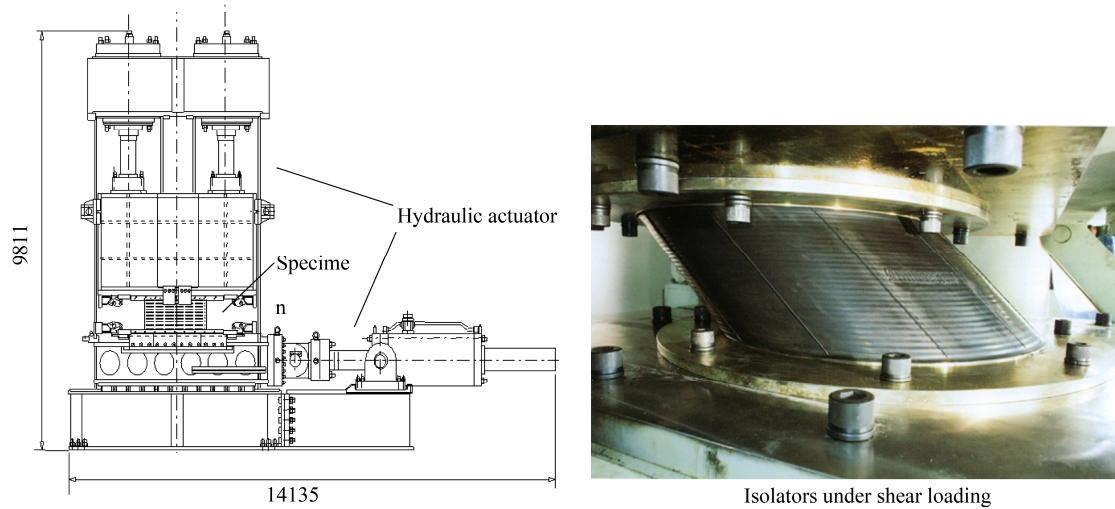


Fig. 7 An example of compression and shear testing machine

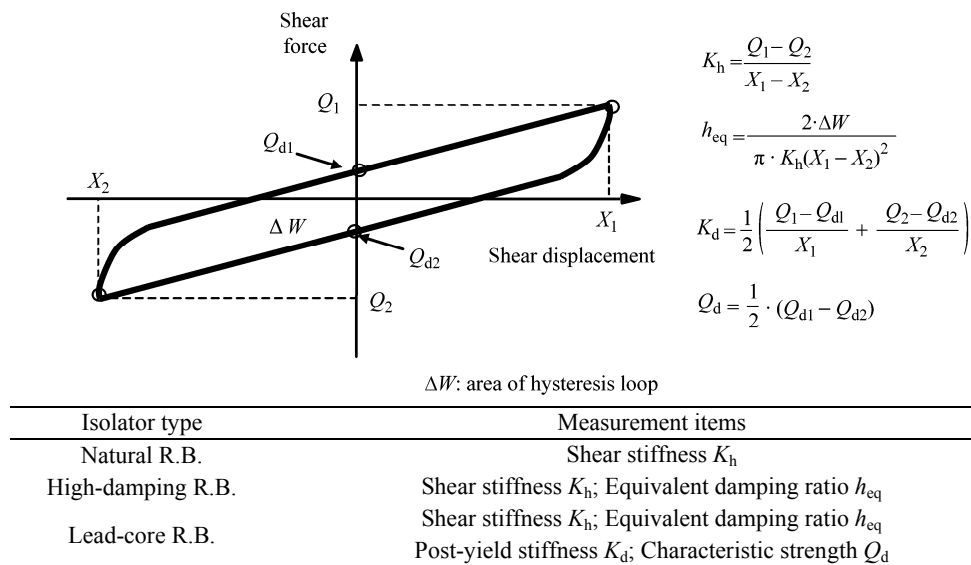


Fig. 8 Definitions of shear properties of isolators

VARIOUS PROPERTIES OF ELASTOMERIC ISOLATORS

There are other important properties of elastomeric isolators which should be considered at design of seismic isolation systems. The properties and test items are shown in Table 3.

Dependencies of Shear Properties

Dependencies of shear properties, such as stiffness and damping ratio, shall be properly evaluated and considered at design of SI systems.

If the isolator has non-linearity in the relationship with shear stress and strain, their shear dependency should be evaluated by testing and counted in the analysis of seismic response. Figure 9 shows the shear strain

dependency of shear modulus and damping ratio of high-damping rubber bearings. The relationship is usually applied to seismic response analysis. Typical numerical model, bi-linear model, for time-history analysis is also shown in Fig. 9. Generally, polymer has significant temperature dependence especially when it has large damping. Therefore, change of stiffness or damping ratio at various temperatures shall be measured and defined by the test. Repeated loading is one of the hot topics in seismic isolation. The existence of the earthquake with long duration time is highlighted with recent major earthquakes in Japan. Some of earthquakes had more than 5 min shaking motion. Considering these earthquakes, the change of the properties by repeated loading gives us important information for design. Figure 10 shows an example of repeated loading test of high-damping rubber bearings. The stiffness, damping ratio and energy dissipation are decreased by the cyclic loading.

Table 3. Other properties of isolators to be considered at design of isolation system

Properties	Test items
Dependency of shear properties	Shear strain dependency
	Compressive stress dependency
	Frequency dependency
	Repeated loading dependency
	Temperature dependency
Ultimate properties	Breaking strain
	Buckling strain
Tensile properties	Tensile yield stress
	Tensile fracture strength
Durability	Ageing
	Creep

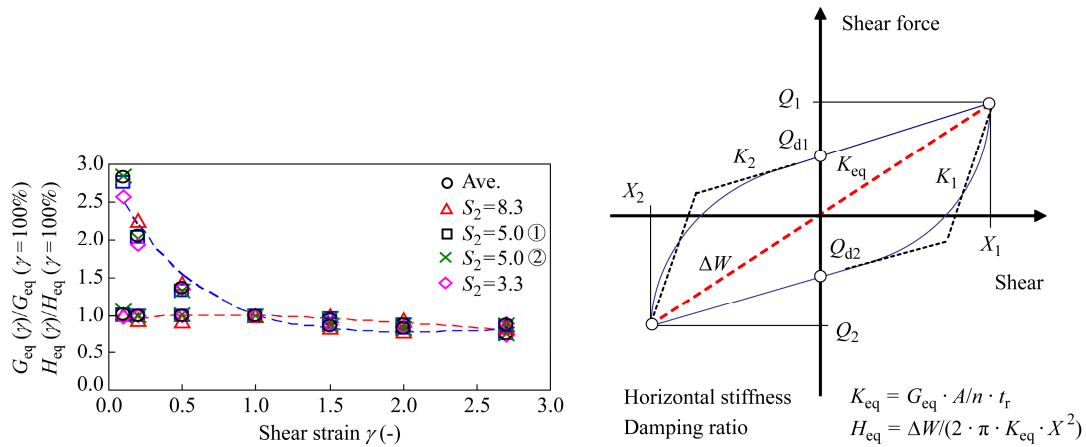


Fig. 9 An example of shear strain dependency test of high-damping rubber bearings

Ultimate Properties

Ultimate properties, defined as breaking or bucking, shall be specified for every isolators by test results, and design displacement of isolators shall be decided based on the ultimate displacement with adequate safety margin. Figure 11 shows typical stress-strain relationship of breaking test. Typically, the breaking strain of isolators in any type exists more than 400% shear strain.

Tensile Properties

Recently, many high-rise buildings are seismically isolated. The typical technical problem in this application is tensile load on isolators during earthquake. Because of the large over-turning moment generated during earthquake in those tall buildings, isolators under walls or at the corner of the buildings tend to have tensile load. Laminated rubber structure is strong in compression but not in tension. The stress-strain relationship in tension is shown in Figure 12. The tensile stiffness is around 1/10 to 1/20 of compression stiffness, and shows sudden

softening beyond certain load, as likely yielding point of steel. And the tensile load during earthquake shall be lower than this “yielding point”. Typically, the allowable tensile stress on the isolators is specified as 1.0 MPa in Japanese code for seismic isolation design, and the tensile yield stress of isolator shall be higher than 1.0 MPa.

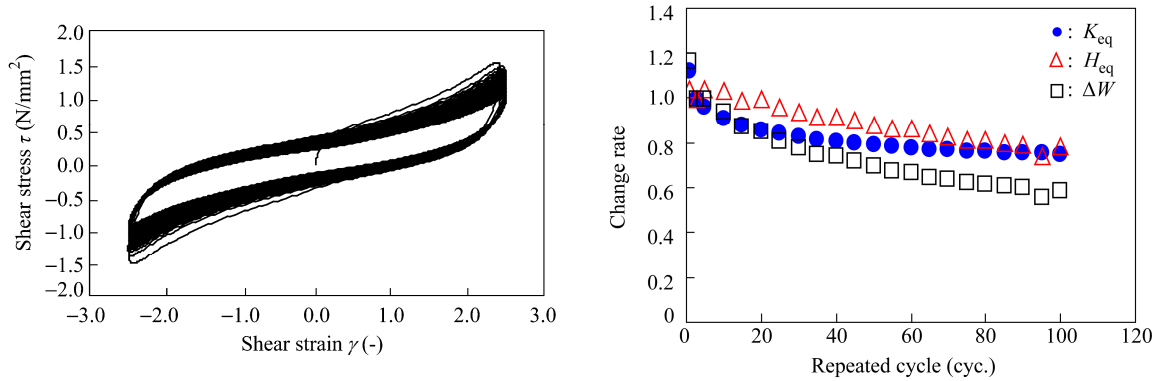


Fig. 10 An example of repeated-loading dependency test of high-damping rubber bearings

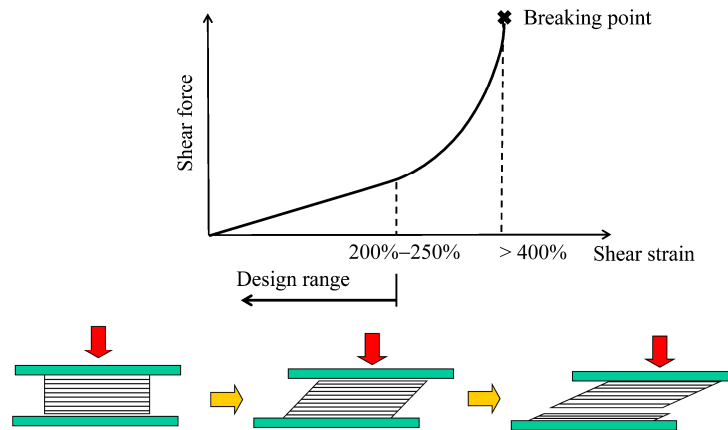


Fig. 11 Ultimate property test of isolators

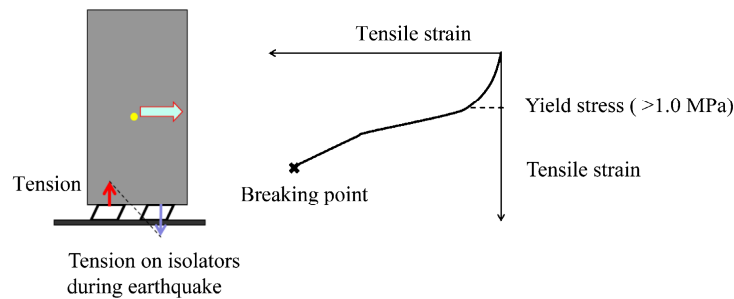


Fig. 12 Tensile property of isolators

Durability

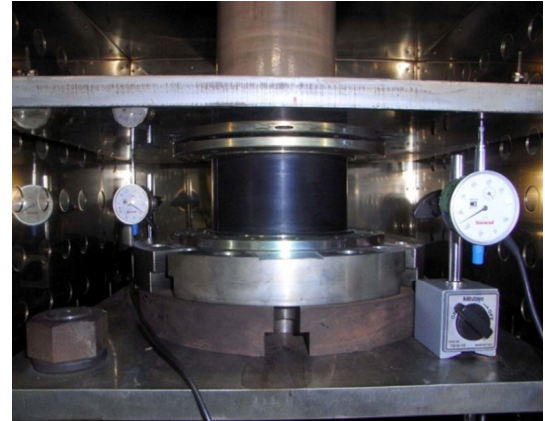
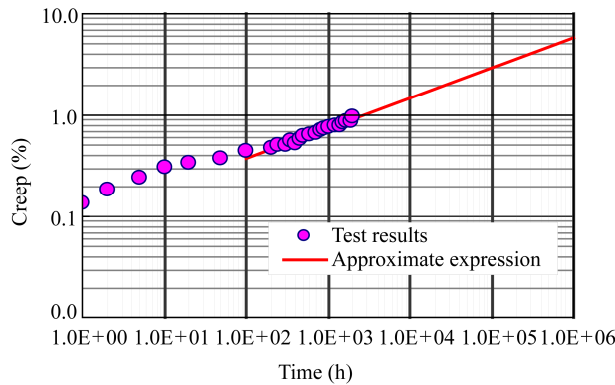
Considering long term usage of buildings or bridges, expected life of elastomeric isolators is long. Therefore, shear properties for expected life should be estimated by appropriate method. Generally, the changes of properties by aging are estimated by heat-accelerated aging testing. The typical value of the change rate of the properties from the initial state after 60 years is around +10% for stiffness, and -10% for damping in case of high-damping rubber bearing as shown in Table 4. Creep characteristics of isolators are evaluated by either normal temperature or heat-accelerated conditions, as shown in Fig. 13. In this case, creep strain of isolator is estimated around 8%. Creep strain depends on the relative thickness of rubber layers and compressive stress on isolators.

Table 4. An example of heat-accelerated aging test of high-damping rubber bearings

Specimen #	G_{eq}	H_{eq}
1	+9%	-10%
2	+10%	-5%
3	+7%	-6%

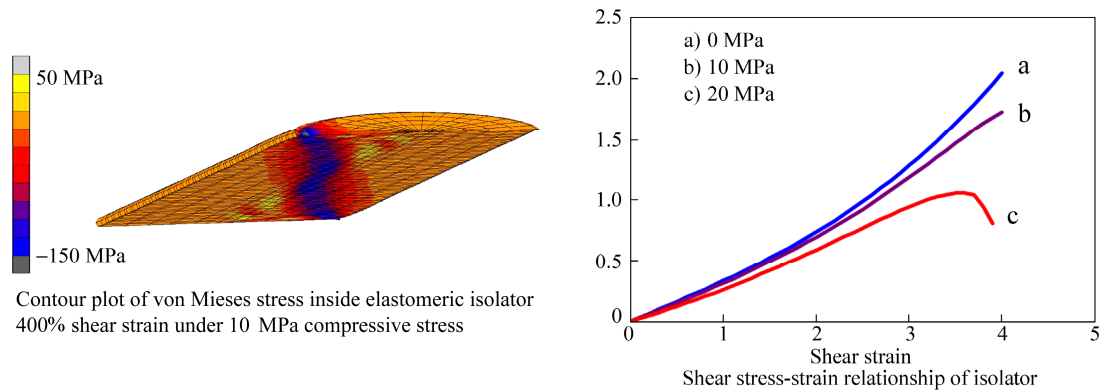
Test isolator: 160 mm dia., $S1 = 35$, $S2 = 5$;

Temperature cond.: $90^{\circ}\text{C} \times 16$ days (equivalent year 60y. under 20°C)

**Fig. 13** Creep test of elastomeric isolators

COMPUTER AIDED ENGINEERING FOR ELASTOMERIC ISOLATORS

Progress in computer technology both in hard- and software enabled high-nonlinear analysis with reasonable time and cost. Large deformation finite element analysis (FEA) of elastomeric isolators has been studied by many researchers (for example^[2]). Figure 14 shows an example of FEA of elastomeric isolators under combined compression-shear loading in contour plot of von Mises stress. The information of stress or strain distribution inside bearings cannot be obtained by experiment. Figure 15 shows comparison of FEA and experiment in hysteresis loops under uni-, and bi-axial cyclic shear loading. The results verified the high accuracy and applicability of the FEA for practical design of isolators.

**Fig. 14** An example of FEA for elastomeric isolators

FUTURE DIRECTION OF SEISMIC ISOLATION AND ELASTOMERIC ISOLATORS

Thus, the seismic isolation is becoming more popular, and will be one of the standard seismic-protection design method. In the 2011 Tohoku District Off the Pacific Ocean earthquake, the SI buildings and bridges performed well and verified the effectiveness of SI without any doubt. And elastomeric isolators are a key device of SI

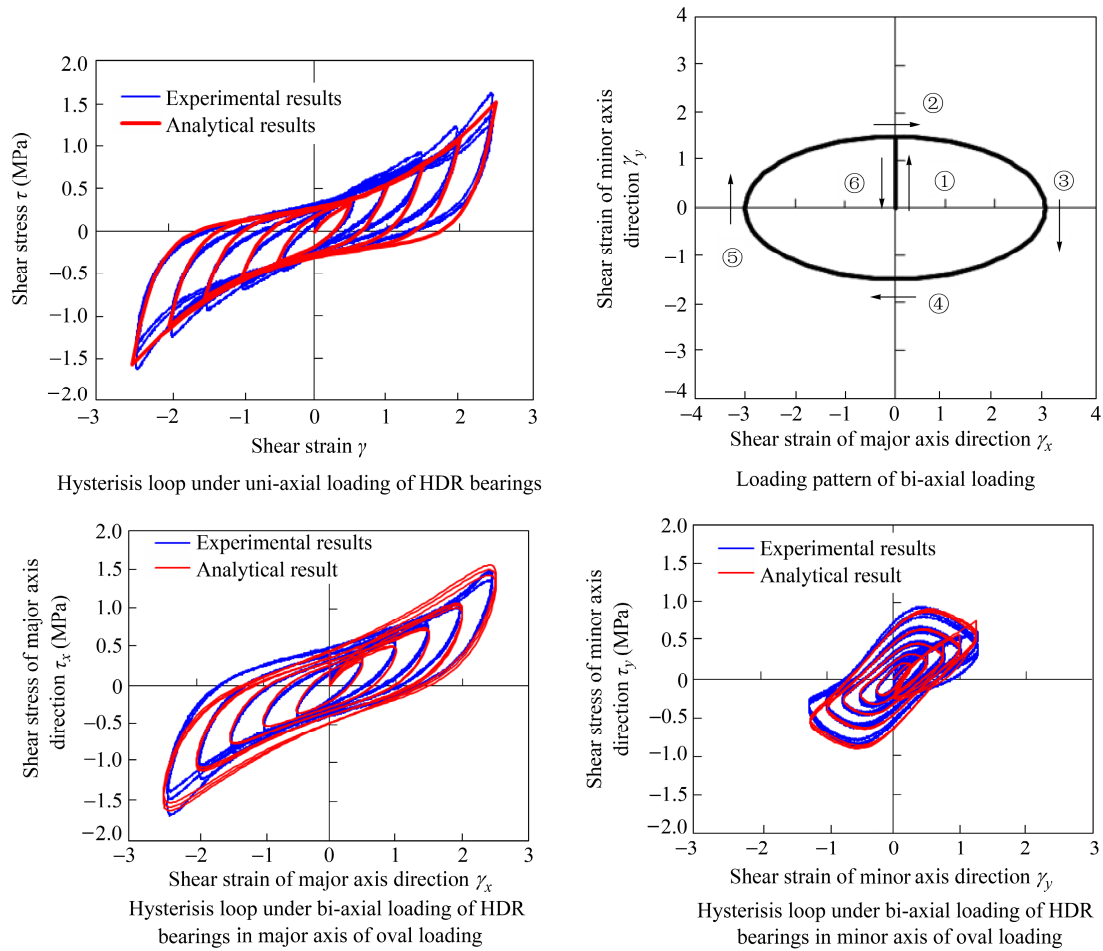


Fig. 15 Comparison of FEA and experimental results of cyclic shear loading in uni-, and bi-axial shear loading

system. Progress of technology of elastomeric isolators in this decade is remarkable. Many important information about characteristics of isolators have been obtained by experiments and standardized for disseminate the SI technologies. In 2005, the first international standard (ISO) for elastomeric isolators, ISO 22762^[3], was issued by the leadership of Japan. Based on the ISO 22762, Japanese Industrial Standard for elastomeric isolators was developed in 2011, as well as the GB 20688-2006 in China. The environment of SI is improved by these standardization. Authors expect further popularization of SI and elastomeric isolators worldwide for protection of properties and human lives through our aggressive activities of promoting the SI technology in every opportunity.

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