PRELIMINARY EVALUATIONS OF AIR TEMPERATURE EFFECTS ON THE RESPONSE OF SEISMICALLY ISOLATED BRIDGES EMPLOYING ELASTOMERIC BEARINGS

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Abstract

Laminated rubber bearing is a common seismic protection device for bridge structures based on its high vertical stiffness, low horizontal and rotational stiffness, and significant lateral restoring capacity. However, the mechanical behavior of elastomers, particularly the material's shear stiffness, is significantly influenced by variations in air temperature. The cyclic behavior of elastomeric isolators is affected by variations in air temperature and this is considered by current seismic codes through requiring upper and lower bound analysis using relevant modification factors. As a result, it significantly impacts the seismic responses of structures employing laminate rubber isolators. However, this aspect is not frequently considered when designing seismic isolation in most locations. This article aims to evaluate the effect of air temperature on the seismic response of isolated bridges. A parametric study, with varying temperature conduction, is carried out. The responses of a seismically isolated bridge are evaluated by the peak value of lateral force and displacement. Results indicate that air temperature has considerable effects on the behavior of rubber isolators and seismic responses of isolated bridges.

Keywords: *Seismic analysis; rubber isolator; temperature dependence; seismically isolated bridges; nonlinear behavior.*

1. Introduction

Earthquakes produce enormous damage and costs, especially to infrastructures such as bridges and buildings. Many creative retrofit solutions have been investigated and developed. Practical applications have been promoted and supervised.

Recently, the use of seismic isolation systems (SIS) has become increasingly common for bridges in earthquake regions. The basic principle of seismic base isolation consists of lowering the lateral stiffness of the bridge structure under strong impacts (i.e., strong earthquakes) and impressive energy dissipation mechanisms [1-3]. Consequently, it significantly reduces lateral forces in the substructures and prevents horizontal drift of superstructures due to earthquakes, thereby ensuring the safety of the structure.

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Lead-plug Rubber Bearing (LRB) and High Damping Rubber Bearing (HDRB) are two primary types of elastomer-based SIS that have traditionally been used over the decades. These devices are made of rubber layers and steel shims, which offer great vertical bearing and horizontal deformation capacities. In order to fully comprehend the mechanical behavior of these devices and accurately predict the response of seismically isolated bridges using them, many scholars have carried out a lot of experimental studies and proposed a variety of representative numerical models. Accordingly, the force-displacement relationship of seismic isolators is interdependent on several parameters and conditions, in particular the architecture and nature of the system's components, the rate of deformation, temperature conditions, level of internal loads/stresses, instantaneous velocity, loading history, the interaction of mechanical properties, contamination and/or aging of components, etc. [1, 4-8]. There are several appropriate hysteretic models that represent the behavior of SIS with differing degrees of sophistication and complexity [1, 9-11]. These models are selected based on the complexity of the structural analysis required, the degree of precision necessary, and the specific mechanical behavior studied. Among them, the nonlinear hysteretic models are the most complex, but they allow for the best and most accurate representation of the actual behavior of certain systems [9, 12]. Although the bilinear model is the simplest nonlinear model, it is also the most widely used for the analysis of isolated structures, especially cases where rubber isolators are employed.

Although the research on elastomeric bearings has been relatively comprehensive and in-depth, the influence of many factors still needs further study, especially the effects of the variation of temperature. It is a fact that the mechanical performance of rubber bearings is severely affected by temperature, which is still not carefully considered in the seismic isolation design and may result in misunderstandings and/or deadly accidents in cold and seismically active regions. In addition, the properties of rubber isolators are closely related to the response of seismically isolated bridge structures. Evaluating the impact of the rubber isolator's temperature sensitivity on the structural response is therefore important from an engineering perspective.

To investigate the effects of such factors, two boundary evaluations, including the upper limit analysis for the maximum shear force and the lower limit analysis for the maximum displacement of the isolation layer, are required by the European [13] and American Seismic Design Codes [14] for the design of isolation structures. These limits are significant for reference and preliminary studies, even for the design in the absence of the test results. Otherwise, evaluating the upper and lower limit properties of the SIS essentially requires a series of expensive bearing temperature dependence tests.

The objective of this study is to evaluate the effects of different air temperature conditions on the seismic performance of rubber isolators. The bilinear model is employed to represent the nonlinear behavior of seismic rubber bearings. To obtain the mechanical properties of rubber bearings under different temperatures, the property modification factors taken according to AASHTO standards are multiplied with the parameter models under normal conditions. The differences in the responses of displacement and lateral force of the isolated bridge structure as well as the hysteresis response of SISs are selected to investigate the effects of temperature on the behavior of the device and the seismic responses of bridges.

2. Effects of temperature on rubber isolator's behavior

2.1. Available experimental results

Many studies conducted experiments on the rubber's behavior at different temperature conditions and found that rubber will harden at low temperatures, resulting in a significant impact on the mechanical properties of the devices [7, 8, 15, 16]. Specifically, the low temperatures have considerable effects on the damping characteristics, yield strength [17, 18], and bearing stiffness in such conditions is almost twice and more than at normal temperatures [19-22].

Generally, the stiffening of rubber under low temperatures mainly occurs in two phases [22-24], including instantaneous thermal stiffening and crystallization, as illustrated in Fig. 1. According to the figure, the time t_1 represents the instantaneous thermal stiffening which characterizes the achievement of thermal equilibrium in the rubber. Between t_1 and t_2, the rubber's stiffness remains practically unchanged. This period essentially depends on the temperature and the chemical composition of the rubber. After the time t_2, an increase in stiffness with exposure time is observed which is due to the crystallization of the elastomer.

Specifically, the instantaneous thermal stiffening is a rapid increase in the stiffness of the elastomer under low temperatures. This time interval strongly depends on the temperature and the thickness of the elastomer [23]. The lower the temperature, the greater the stiffening. The crystallization occurs when the elastomer is subjected to low temperatures for long periods, (i.e., after instantaneous thermal stiffening is reached [23]). It corresponds to a gradual increase in stiffness which varies in particular according to the temperature and the time of exposure to it as well as the type and chemical composition of the elastomer. This phenomenon is completely reversible and disappears with the increase in temperature. For crystallization occurring at 0°C, crystallite melting begins at about 6°C and ends at 16°C [25].

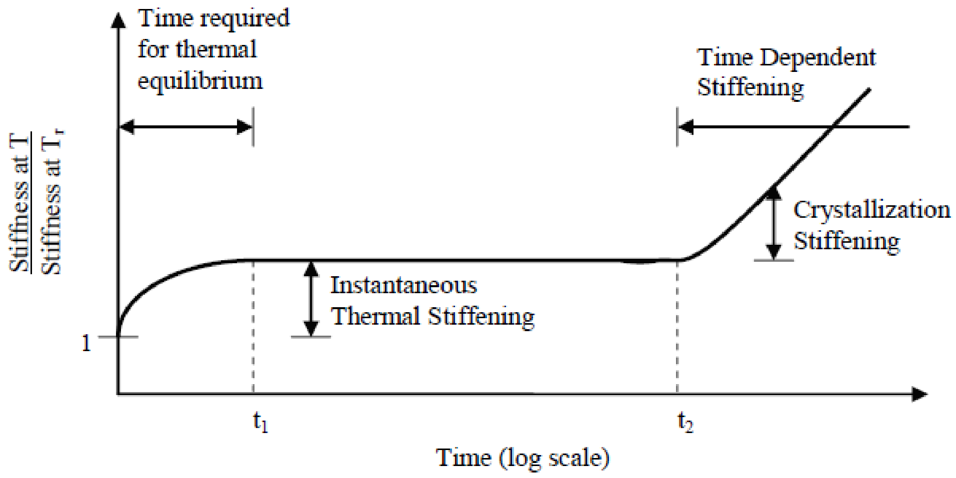

Fig. 1. Rubber's behavior in low temperatures, taken from Constantinou et al. [23].

Roeder et al. [24] carried out experimental studies to evaluate the effects of low temperatures on the behavior of natural rubber and neoprene. The specimens were subjected to temperatures ranging from -10°C to -50°C for conditioning periods of between 1 and 24 days. The results indicate an increase in stiffness in the first 24 hours due to instantaneous thermal stiffening, except at a temperature of -50°C for which the elastomer underwent a glass transition. Kim et al. [26] conducted an experimental study to investigate the seismic performance of a rubber bearing (RB) and a lead-plug rubber bearing (LRB) at low temperatures. The RB was cooled to -48°C and the LRB to -32°C and held at these temperatures for a few days to ensure that the center of the insulators reached the target temperatures. The results showed an increase in the effective stiffness (K_{eff}) of the RB of about 112% compared to 20°C, while the LRB showed increases of about 87% for elastic stiffness and 32% for post-elastic stiffness.

Yakut and Yura [22] carried out an experimental study where the parameters influencing the performance of laminated elastomer bearings at low temperatures were investigated with neoprene and natural rubber. The exposure temperatures were -10°C, -20°C, and -30°C for conditioning periods ranging from 1 to 21 days. These results show that all specimens provided significantly higher stiffening at -30°C than at higher temperatures of -20°C and -10°C and the longer the exposure duration, the greater the stiffening. Further, neoprene is more sensitive to crystallization than natural rubber. Fuller et al. [19] experimentally studied the phenomenon of crystallization at low temperatures of two high-damping natural rubber compounds (HDNR) used in seismic isolation techniques. The elastomers were subjected to a temperature of -20°C and a shear deformation amplitude of 35%. The conventional high-damping rubber compound shows a significant increase in shear modulus after approximately 3 days of exposure to -20°C due to the crystallization of the elastomer. Meanwhile, the modified compound lengthens the induction period to about 20 days and delays the onset of crystallization.

Constantinou et al. [23] performed combined compression and shear tests on RB and LRB to determine the effect of temperature variation on their mechanical properties. Specimens were tested first at 20°C after 48 hours of conditioning, then at -26°C for 48 hours. The results show that for the RB, the effective stiffness increases by about 42% after 48 hours of conditioning at -26°C. For the LRB, the results show increases of about 53% in effective stiffness and 37% in post-elastic stiffness. Cardone and Gesualdi [8] studied the behavior of elastomers used in isolated structures under different air temperatures. The tests were conducted in two parts. In the first part, the specimens were subjected to temperatures ranging from 40°C to -20°C (specimen A) then a reversal from -20°C to 40°C (specimen B) for exposure times varying between 30 and 60 minutes, in order to evaluate the behavior of devices. In the second part, the elastomers were subjected to temperatures of -10°C and -20°C for conditioning times between 1 and 24 hours, in order to investigate crystallization at low temperatures. The results show that there is no deference between specimens A and B, indicating a negligible sensitivity of the cyclic behavior to the effect of the temperature history of tests performed. The results also indicate that as the temperature decreases the maximum stress levels and the areas of the hysteresis curves increase, which become more accentuated when the temperature drops below 0°C.

Generally, the obtained results of these tests all have the same tendency of increasing the lateral stiffness of rubber bearing at low temperatures due to instantaneous thermal stiffening, for both elastic and post-elastic deformation states. This phenomenon may have a significant influence on the device’s behavior, thereby the response of seismically isolated bridge structures, and should be carefully considered in design.

2.2. Specifications of seismic design standards

The effect of variations in system properties on the bridge seismic response can be achieved by performing a bounding analysis where two analyses are performed, one using minimum expected system properties and one using maximum system properties such that displacements and forces can be bounded, as shown in Fig. 2. Accordingly, two analyses will be performed for summer (decreased device stiffness leading to larger displacements) and winter (higher forces due to increased stiffness) conditions, respectively. This bounding approach has been adopted in some standards [14, 27]. However, several standards are not clearly presented [13, 28] or not mentioned [29].

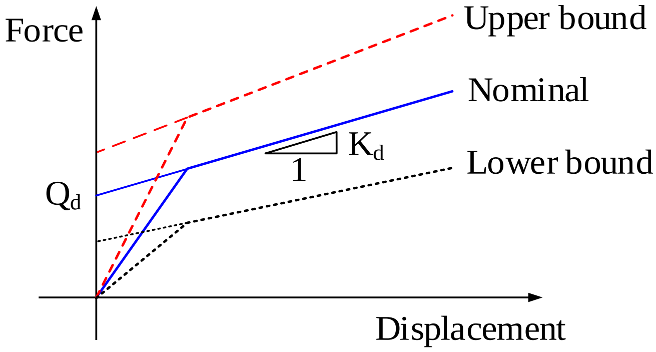

Fig. 2. Maximum and minimum properties of SIS for analysis [14].

According to the bounding analysis approach, the determination of lower and upper bound can be achieved by multiplying the nominal properties of the bilinear force-displacement relationship of the isolation system (i.e., the resistant characteristic Q_d and the post-elastic stiffness K_d) by the modification factors of the maximum and minimum properties, denoted by λ_{max} and λ_{min}, to obtain the bounding values to be used in the analysis. Values for these factors are often obtained from the test.

Table 1. Maximum value of property modification factor for temperature [14]

Minimum Temp. for design (°C)	Q_d			K_d		
	HDRB[a, c]	HDRB[b, c]	LDRB[b, d]	HDRB[a, c]	HDRB[b, c]	LDRB[b, d]
21	1.0	*1.0*	1.0	1.0	*1.0*	1.0
0	1.3	*1.3*	1.3	1.2	*1.1*	1.1
-10	1.4	*1.4*	1.4	1.4	*1.2*	1.1
-30	2.5	2.0	1.5	2.0	1.4	1.3

[a] Large difference between scragged and unscragged properties. A large difference is one in which the unscragged properties are at least 25% more than the scragged ones.

[b] Small difference between scragged and unscragged properties.

[c] High-Damping Rubber Bearing (HDRB).

[d] Low-Damping Rubber Bearing (LDRB).

Generally, the minimum value of the modification factor is less than or equal to unity. Due to the fact that most values of λ_{min} proposed are close to unity, the lower bound of the system properties is often considered to be the same as their nominal values (under normal temperature conditions). In place of the test results (unavailable test values), the values given in Table 1 may be used [14].

3. Seismic response of base isolation structure under different temperature

3.1. Description of the analysis model

According to the above discussions, the influence of temperature on the mechanical properties of rubber bearings should not be ignored. This section conducts studies on bridge structures using rubber bearings as shown in Fig. 3(a).

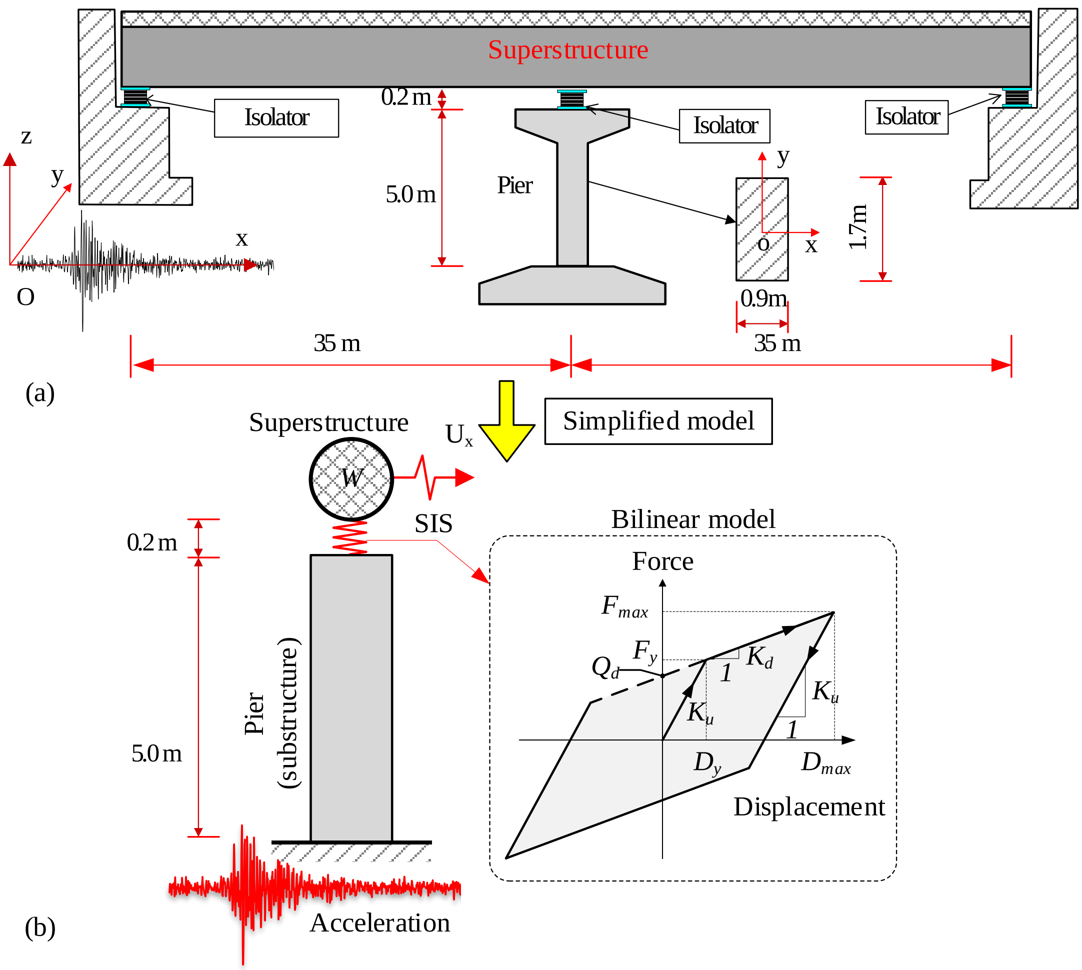

Fig. 3. Seismically isolated bridge structure model (case study).

It assumes that the seismic weight of the bridge superstructure is W_{sup} = 16000 kN. The pier is 5.0 m in height and 0.9 m × 1.7 m of the cross-section. The pier is made of reinforced concrete B20 (TCVN 5574:2018), the material properties include Young's modulus E = 27000 MPa, the weight density ρ = 23.56 kN/m^3, and the Poisson ratio υ = 0.2. The pier is rigidly constrained at the bottom.

In the preliminary analysis, the isolated bridge can be modeled by a simplified model (as illustrated in Fig. 3(b)), where all the isolation units are lumped into a unique equivalent isolator. The superstructure is represented by the seismic weight W. Actually, the method of using the simplified model is also recommended by most design standards and researchers, especially in the preliminary design step.

Without loss of generality, the bridge is assumed to be located in Son La - Vietnam, supported on soil class II and 5% damping (TCVN 11823:2017). The elastic response spectrum of location is determined according to TCVN 11823:2017 and plotted in Fig. 4(d).

Table 2. Earthquake records were selected for analyses

Earthquake	Station	Mw	Hypocenter distance (km)	PGA (g)
El Centro, 1940-05-19	CA - Array Sta 9; Imperial Valley Irrigation, US	6.9	12.2	0.355
Kobe, 1995-01-16	Nishi-Akashi, Japan	6.9	19.9	0.51
Northwest China, 1997-04-11	Jiashi, China	6.1	27.7	0.3

To perform nonlinear time-history analysis, a suite of three recorded ground motions is selected and employed, as shown in Table 2. These accelerograms are scaled by the method proposed in references [30, 31] to match the target spectrum of Son La, which was determined according to TCVN 11823:2017. Time-history accelerations of these motions are plotted in Fig. 4(a-c). Fig. 4(d) presents the response spectra of selected and scaled accelerograms, indicating a good agreement between the response spectrum of scaled accelerograms and the target response spectrum. These accelerograms are then used as input functions of time-history ground acceleration in the numerical model.

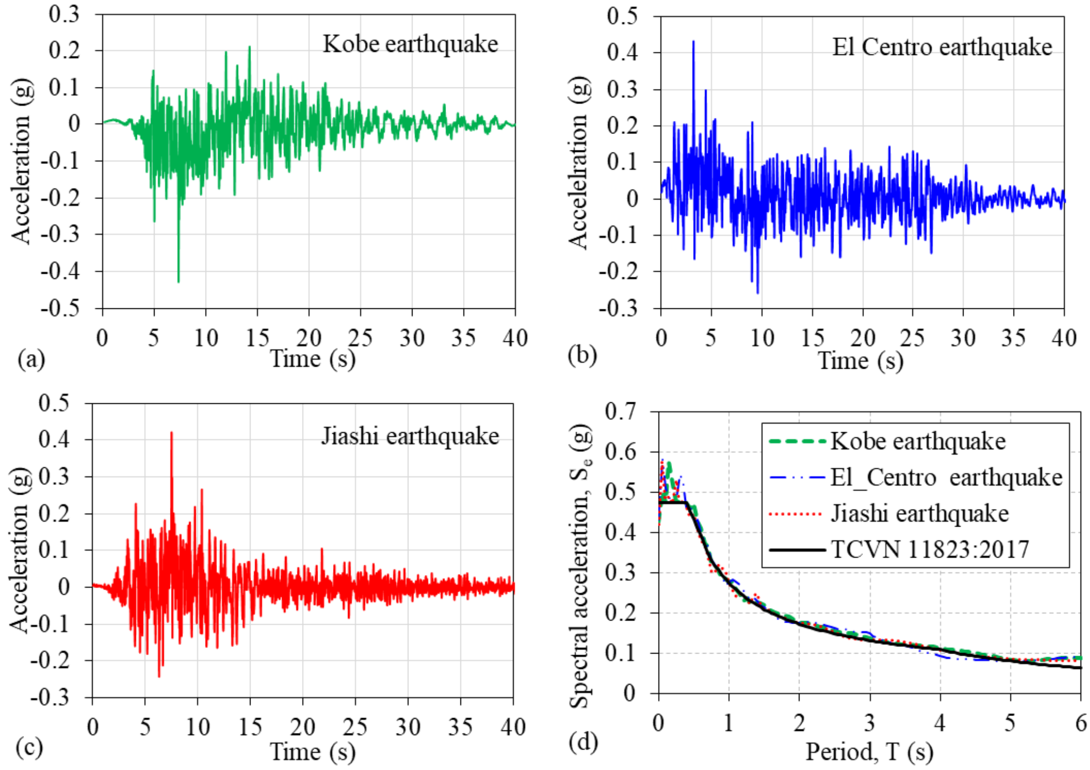

Fig. 4. Earthquake motions used for analyses.

The isolator layer is composed of High Damping Rubber Bearings (HDRB), which are ideally modeled by the hysteresis bilinear model, including the constitutive parameters of Q_d = 400 kN, K_d = 7.15 × 10^3 kN/m, and the initial elastic stiffness $K_u = 100.K_d$ as recommended by Naeim and M. Kelly [1]. SAP2000 software is employed to conduct a set of nonlinear time-history analyses.

In the absence of experimental results, this preliminary study uses the modification factor of temperature specified in the AASHTO standard and the experimental results conducted by D. Cardone et al. [8], for HDRB, within the suitable range from -10°C to 40°C (i.e., -10°C, 0°C, 21°C, 30°C, 40°C). The temperature range used in this analysis ensures coverage of the common temperature range in all regions of Vietnam. Further, the analyses at upper bound (i.e., at -10°C) and lower bound (i.e., at 40°C) in this article are meaningful for regions with harsh weather conditions and similar seismic hazard, even for several areas in Vietnam (some areas have recorded temperatures about -5°C and/or 41°C in history). The bilinear models that represent the isolation systems are illustrated in Fig. 5 for three different levels of the air temperature.

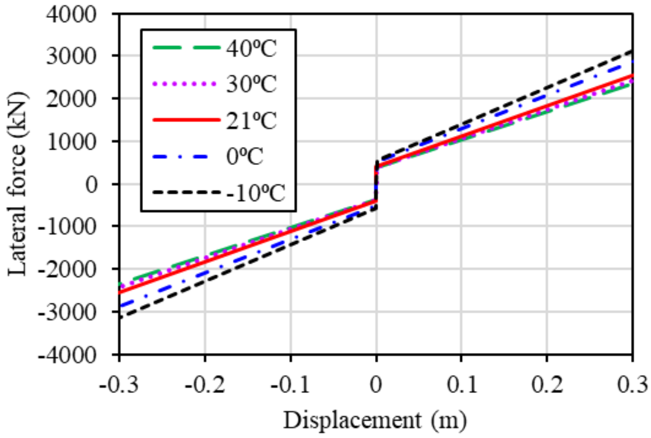

Fig. 5. Representative bilinear model of isolators.

3.2. Analysis results

In the design of seismically isolated bridges, the maximum displacement and lateral force of isolators are important features to evaluate whether the isolation structure reaches the limit states. Generally, seismic isolation systems offer great seismic performance by reducing acceleration and lateral force at the bridge substructure but increasing lateral displacement at the superstructure. However, the significant differences in the instantaneous mechanical properties of isolation bearings caused by the variation of temperature (stiffness and dissipation capacity) may considerably change the isolating efficiency of the system.

Figure 6 shows the difference in time-history responses of displacement and lateral force of seismically isolated bridges using SIS at different temperatures.

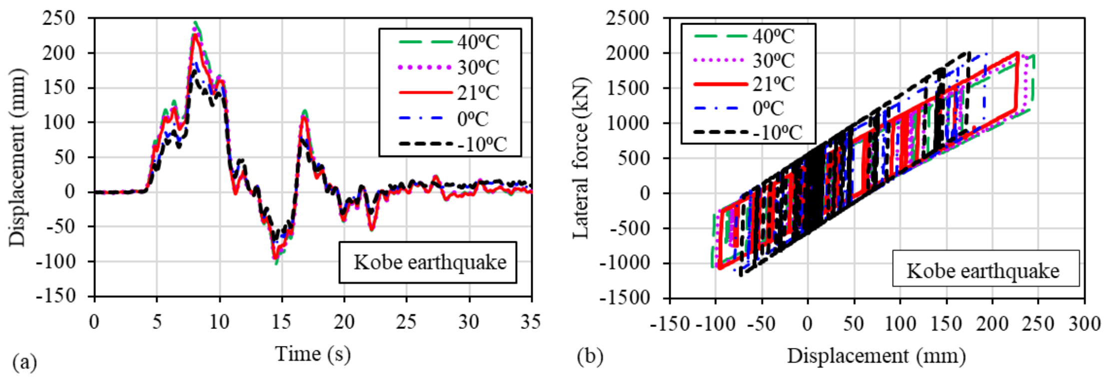

Fig. 6. Effect of temperature on time-history response of seismically isolated bridge subjected to Kobe's earthquake.

It can be found that the temperature changes have a significant impact on the nonlinear behavior of rubber bearings and also the seismic responses of isolated bridge structures. Particularly, the decrease in temperature reduces the displacement of the superstructure and increases the lateral force at the isolator level. This result is consistent with the discussions above that low temperatures will increase the stiffness of the isolation system, resulting in a decrease in the displacement. More specifically, the displacement at 40°C (green dash) is significantly larger than that at -10°C (black dash) (i.e., 245.0 mm versus 174.5 mm), while the increase in lateral force is quite small (it seems to be negligible - see Fig. 6(b).

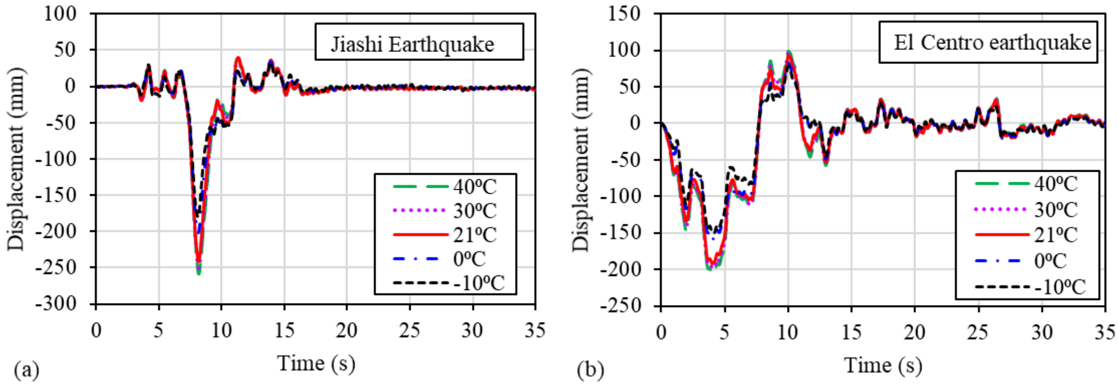

Fig. 7. Effect of temperature on time-history responses of seismically isolated bridge.

Similar results are obtained in Fig. 7(a) and Fig. 7(b), where the isolated bridges subjected to two other earthquake motions of Jiashi and El-Centro, respectively.

In addition, the comparison of obtained responses is summarised in Fig. 8 for three earthquake motions. It clearly shows the decrease of displacements when the temperature reduces, while the lateral force shows an increase trending as the temperature decreases even if the increase's rate is not significant.

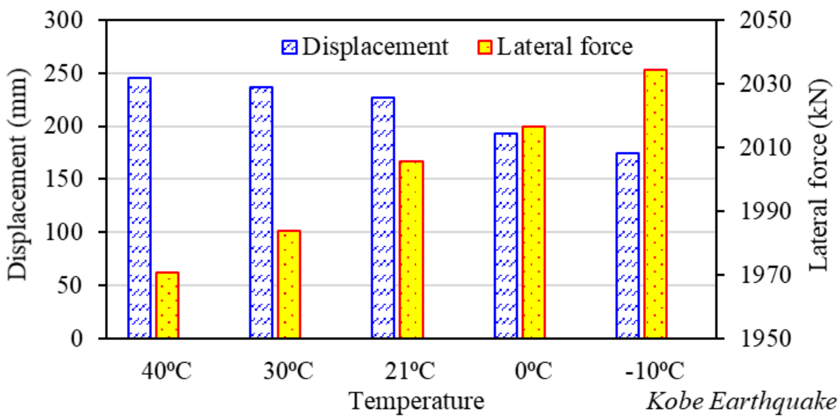

Fig. 8. Effect of temperature on peak response of displacement and lateral force.

Table 3 presents detailed results of analyzing the influence of different temperature conditions on the earthquake response of structures. As observed in the table, the variation of structural displacement at each temperature level is quite similar for all three accelerograms, about -25% at -10°C and +7% at 40°C compared with the results at 21°C. It should also be noted that the rate of displacement change at high temperatures is lower than that at low temperatures (-17% at 0°C and +7% at 40°C compared with the results at 21°C). The obtained results suggest that it is necessary to analyze the effects of temperature on rubber seismic bearings, especially low temperature conditions.

Table 3. Effect of temperature on seismic peak response of isolated bridges

Earthquakes	Temperature (T)	D_{max} (mm)	D_{max} (T)/D_{max} (21°C)
Jiashi	40°C	258.7	107.2%
	30°C	250.5	103.8%
	21°C	241.3	100%
	0°C	202.2	83.8%
	-10°C	180.1	74.6%
El Centro	40°C	205.3	106.9%
	30°C	198.5	103.4%
	21°C	192.1	100%
	0°C	158.0	82.3%
	-10°C	149.9	78.0%
Kobe	40°C	245.0	107.8%
	30°C	236.9	104.3%
	21°C	227.2	100%
	0°C	192.9	84.9%
	-10°C	174.5	76.8%
		F_{max} (kN)	F_{max} (T)/F_{max} (21°C)
	40°C	1970.6	98.3%
	30°C	1983.8	98.9%
	21°C	2005.7	100%
	0°C	2016.5	100.5%
	-10°C	2034.4	101.4%

3.3. Discussion

It is observed that temperature variation shows a significant influence on the nonlinear behavior of rubber bearings. In the framework of this study, when the temperature decreases (from 40°C to -10°C), the stiffness (both initial elastic stiffness and post-elastic stiffness) and the characteristic strength incease significantly, leading to a significant change in the device’s behavior. As a result, the seismic responses of structures are considerably changed. Further, the lower bound characteristic of SIS leads to a significant increase in displacement compared to the upper bound. For the design procedure, the absence of consideration of these limits may lead to errors in the limit states and stability of the bearing. Therefore, this phenomenon should be considered in the design, especially in the regions with large temperature variations.

4. Conclusion and perspectives

Seismic rubber isolators are an effective solution for the seismic-resistant design of bridges and widely applied in practice. However, its mechanical properties are affected by changes in air temperature. As observations, a decrease in temperature leads to an increase in material stiffness, which leads to an increase in the lateral stiffness of the device and a decrease in the displacements of the superstructures. The analysis results in the article show that the lateral displacement of the structure between the lower bound (40^{o}C) and upper one (-10^{o}C) significantly differs by up to 33%. This result has important implications in determining limit states when designing seismic isolation bearings.

In the framework of this study, the modification properties factors are taken from the recommendations of AASHTO standards. Available experimental results showed that each rubber class has its factor. Further experimental studies need to be carried out to determine the appropriate factors for application in Vietnam.

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ĐÁNH GIÁ SƠ BỘ TÁC ĐỘNG CỦA NHIỆT ĐỘ ĐẾN PHẢN ỨNG CỦA KẾT CẤU CẦU SỬ DỤNG GỐI CÁCH CHẤN CAO SU

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Tóm tắt: Gối cao su nhiều lớp là thiết bị chống động đất phổ biến cho các công trình cầu dựa vào độ cứng dọc trục lớn, độ cứng ngang và độ cứng xoay nhỏ cũng như khả năng phục hồi ấn tượng. Tuy nhiên, đặc tính cơ học của chất đàn hồi, đặc biệt là độ cứng khi chịu cắt của vật liệu, bị ảnh hưởng đáng kể bởi sự thay đổi nhiệt độ không khí. Do đó, ứng xử khi chịu tải trọng lặp của gối cách chấn cao su bị ảnh hưởng bởi sự thay đổi nhiệt độ không khí và đã được chỉ định trong các tiêu chuẩn thiết kế hiện hành thông qua việc yêu cầu phân tích giới hạn trên và giới hạn dưới bằng cách sử dụng các hệ số hiệu chỉnh. Kết quả là nó có tác động đáng kể đến phản ứng động đất của kết cấu cầu cách chấn. Tuy nhiên, nội dung này ít được quan tâm đến trong công tác thiết kế gối cách chấn ở hầu hết các khu vực. Bài báo này nhằm mục đích đánh giá sơ bộ ảnh hưởng của nhiệt độ đến phản ứng động đất của kết cấu cầu cách chấn. Nội dung nghiên cứu tham số, với điều kiện nhiệt độ khác nhau, được thực hiện. Phản ứng động đất của kết cấu cầu cách chấn được đánh giá bằng giá trị cực đại của lực cắt tại trụ cầu và chuyển vị ngang tại mặt cầu. Kết quả cho thấy nhiệt độ không khí có ảnh hưởng đáng kể đến ứng xử của gối cách chấn cao su và phản ứng động đất của kết cấu cầu.

Từ khóa: *Phân tích động đất; gối cách chấn cao su; ảnh hưởng của nhiệt độ; gối cách chấn; ứng xử phi tuyến.*

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