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EXPERIMENTAL AND NUMERICAL STUDY OF SPHERICAL SLIDING BEARING (SSB) PART 3: SEISMIC RESPONSE

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Abstract

SSB, a type of double concave friction pendulum bearing (DCFPB), is commonly used in isolated structures in Japan and the accuracy of the proposed friction models of it are usually validated by displacement controlled tests. However, the validation of the accuracy of their response displacement under earthquakes, which is very important for isolation system design, is always neglected during the validation of the friction models. Especially for using a constant friction coefficient in response analysis, whether it is applicable and how much will be the error of response displacement are still unknown. In this study, three friction models introduced in part 2 (a precise model with fully consideration of pressure, velocity and temperature dependencies, a simplified model simplified from the precise model and a constant model with constant friction coefficient), which were comprehensively validated by unidirectional displacement controlled dynamic tests, are used. Unidirectional response analysis of a rigid-body structure with DCFPBs were conducted using the three friction models. 8 earthquake records with various peak ground velocity, duration time and field distance were selected and they were scaled to records with peak ground velocity equals 0.25m/s, 0.50m/s, 0.75m/s and 1.00m/s as the inputs of the response analysis. The accuracy of the simplified model and the constant model on the response analysis was validated by comparing with the analysis results of the precise model. As a result, the simplified model can give reliable simulation, while the constant model will tend to underestimate the maximum response displacement of the bearing when the peak ground velocity of the input earthquake is larger than 0.5m/s, which is very dangerous for the seismic isolation design.

In addition, in previous studies, the response analysis of structures isolated with DCFPBs commonly used friction coefficient that only depends on velocity or even constant friction coefficient. However, the value of friction coefficient is also highly related to pressure and temperature. Also, in some cases of experimental design and seismic isolation system design, because of the limitation of testing machines or finance, it is important for designers to know whether certain dependency of friction can be ignored and if it is ignored, how much will be the influence. Therefore, another purpose of this study is to clarify the influence of velocity and temperature dependency on the seismic response of DCFPBs installed beneath isolated structures. A parametric study was held on the unidirectional response analysis using the precise model in order to investigate the influence of the velocity and temperature dependency on the behavior of DCFPBs under earthquakes. The result indicates that if the temperature dependency is neglected, large error in displacement or restoring force simulation may occur. For instance, there will be a high possibility that the maximum displacement of the bearing is underestimated, which is very dangerous for the seismic isolation design. If the velocity dependency is not considered in the response analysis, obvious error will occur under small earthquake intensity, however, the difference on the behavior of DCFPB under large earthquake intensity is small.

Keywords: Double concave friction pendulum bearing; Response analysis; Friction dependencies; Parametric study

1. Introduction

Double concave friction pendulum bearings are commonly used in isolated structures and the accuracy of the proposed friction models of them are usually validated by displacement controlled tests. However, the validation of the accuracy of their response displacement under earthquakes, which is very important for isolation system design, is always neglected during the validation of their friction models. Especially for using a constant friction coefficient in response analysis, whether it is applicable and how much will be the error of response displacement are still unknown.

In order to investigate the accuracy of the simplified model and the constant model on estimating the behavior of a DCFPB under a structure during earthquakes, as well as to investigate the influence of velocity and temperature dependency on the behavior of the DCFPB, a unidirectional mechanical model of a rigid-body structure with DCFPB is introduced in this part as shown in fig. 1.

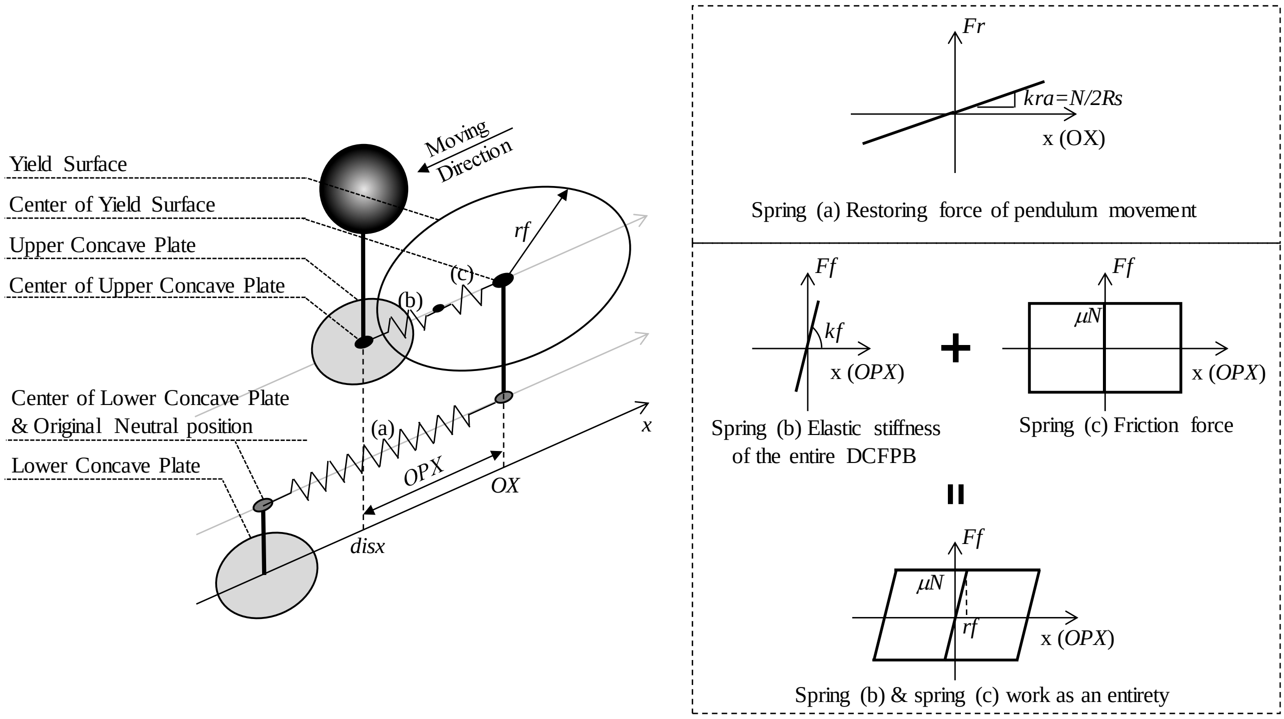


Fig. 1 – Unidirectional mechanical model of a rigid-body structure with DCFPB

In fig. 1, the center of the lower concave plate is taken as the original neutral position. The stiffness of the upper structure is considered as infinite in order to make the behavior of the DCFPB clearer. The boundary of whether the sliding between the slider and the concave plate will happen or not is considered as a yield surface with a radius r_f [1, 2]. *OX* is the center of the yield surface, *disx* is the displacement of the upper structure relatives to the center of the lower concave plate and OPX is the distance in between. The internal forces of the DCFPB are considered as three springs: spring (a), spring (b) and spring (c). Spring (a) represents the restoring force of the pendulum movement. k_{ra} is the stiffness, *N* is the vertical force acts on the DCFPB and R_s is the spherical radius of the upper and lower concave plates. In this study, a DCFPB with the slider diameter equals 400mm is set and a vertical load that can provide 60MPa pressure on the slider surface is applied, therefore k_{ra} equals 0.838kN/mm. *OX* is considered to be the plastic displacement between the upper and lower concave plate, which is the displacement removing elastic displacement of the bearing. Spring (b) represents the elastic stiffness of the entire DCFPB with a value k_f=1900kN/mm based on experimental results. Spring (c) represents the friction force between the slider and two concave plates. Spring (b) and spring (c) work as an entirety to simulate the friction force. When there is no sliding, the friction force is represented by the spring (b) and by the friction models introduced in part 2 during sliding.

2. Response analysis of a rigid-body structure with DCFPB

8 earthquakes with different peak ground velocity (PGV), duration time and field distance were selected as shown in Table 1 as input earthquake motion. The PGV in the table is obtained from the component with the largest peak ground velocity in the horizontal direction of each earthquake record.

Table 1 – Input earthquake motion

Earthquake			Station		*PGV*	Duration	Field
No.	Year	Name	Full name	Abv.	m/s	s	Far/Near
1	1995	Kobe	JMA Kobe	JKB	0.893	30	Far
2			Nishi-Akashi	KNA	0.373	41	Near
3	1999	Chi-Chi	TCU129	TC1	0.554	90	Near
4	1994	Northridge	Canyon Country-WLC	NCC	0.449	20	Far
5	1989	Loma Prieta	Gilroy Array	LPG	0.447	40	Near
6	1979	Imperial Valley	Delta	IVD	0.330	100	Near
7	2011	Tohoku	JMA Sendai	TSD	0.545	180	Near
8			JMA Ishinomaki	TIM	0.376	300	Near

In addition, equations of motion at step *i* which release the unbalanced force is used:

$$accx(i) = -\frac{gaccx(i) + \frac{QFX(i-1)}{mass} + c\times(velx(i-1) + 0.5\times accx(i-1)\times dt) + \frac{k(i-1)}{mass}\times(velx(i-1)\times dt + (0.5-\beta_c)\times accx(i-1)\times dt^2)}{1 + 0.5\times c\times dt + \frac{\beta_c\times k(i-1)\times dt^2}{mass}} \tag{1}$$

$$velx(i) = velx(i-1) + 0.5\times(accx(i-1) + accx(i))\times dt \tag{2}$$

$$disx(i) = disx(i-1) + velx(i-1)\times dt + (0.5-\beta_c)\times accx(i-1)\times dt^2 + \beta_c\times accx(i)\times dt^2 \tag{3}$$

In which *accx*(*i*) is the acceleration of the upper structure relatives to the lower concave plate, *gaccx*(*i*) is the ground acceleration at step *i*, *QFX*(*i*) is the total restoring force of the DCFPB, *mass* is the mass of the rigid body which equals the mass that can provide 60MPa pressure on the slider surface, *c* is the damping coefficient which is set as 0, *velx*(*i*) is the velocity of the upper structure relatives to the lower concave plate, *dt* is the time interval of each step which equals 0.0025s (this value is selected based on the error validation and the time consumption), *k*(*i*) is the stiffness of the system at step *i* and β_c is the constant value which equals 0.25.

A flow chart of the response analysis a SDOF (single degree of freedom) system based on precise model is shown in Fig. 2 for a rigid-body structure with DCFPB. In which, *n* is the serial number of the monitor points, *mp*(*n*) is the coordinate of monitor point n on the lower concave plate, *r* is the side length of a square that has the same area as the slider surface, *q*(*i*,*n*) is the heat flux generated by friction heating at monitor point *n* at step *i* and σ is the average pressure at the slider surface which is set as 60 Mpa during excitation. For each step, firstly, the motion of the system is calculated by equation (1) ~ (3). Secondly, the sliding status will be judged. Thirdly, the friction characteristics will be calculated based on the friction model in traduced in part 2 and the mechanical model of DCFPB introduced in Fig. 1. Finally, the total restoring force of the bearing will be obtained.

In the response analysis, the judgement of the sliding status is considered by the method of yield surface [1, 2]. Only when the displacement between the upper structure and the center of the yield surface is larger than the radius of the yield surface, the bearing will slide.

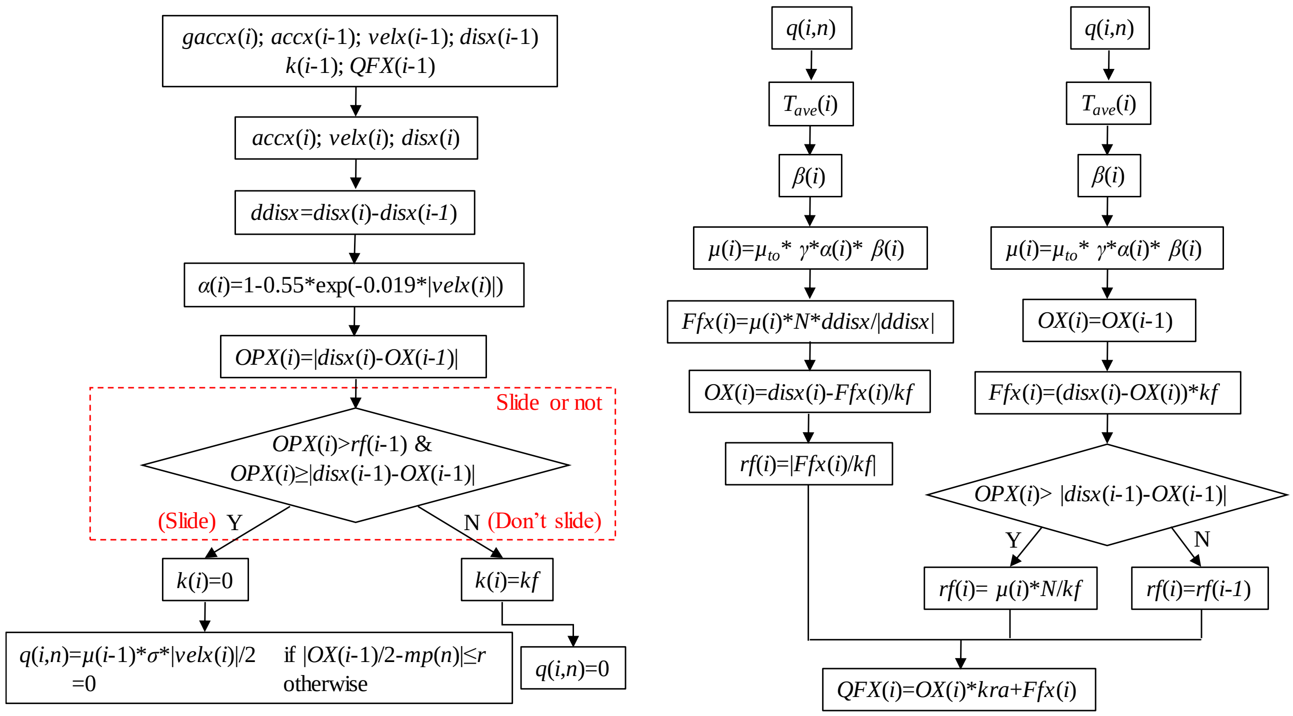
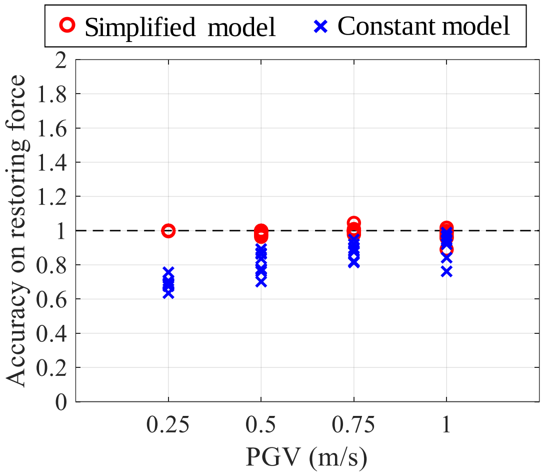


Fig. 2 – Flow chart of the response analysis of a SDOF system based on precise model

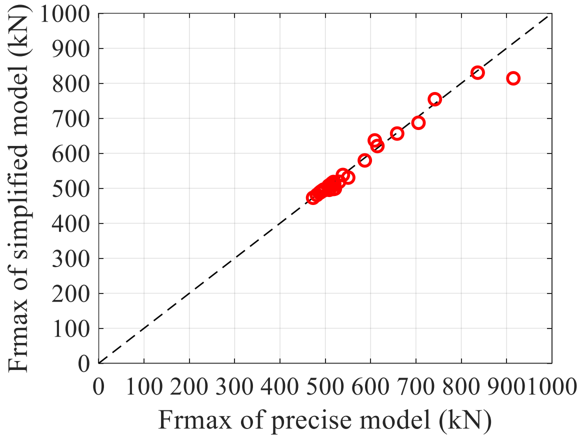
3. Accuracy of the simplified model and constant model on the response analysis

The accuracy of the simplified model and the constant model under sinusoidal displacement variation have already been discussed in part 2. However, their accuracy under earthquake response analysis is still not clear. In order to clarify the accuracy, response analyses based on simplified model and constant model are conducted by inputting the 8 earthquakes shown in Table 1 and the maximum restoring force and the maximum displacement of the analysis results are compared with the results of the analyze based on the precise model. In order to include a larger range of earthquake intensity, each earthquake is scaled so that the peak ground velocity equals 0.25m/s, 0.50m/s, 0.75m/s and 1.00m/s separately.

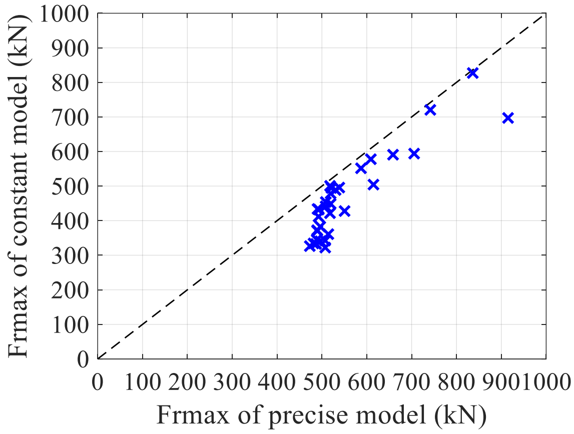
3.1 Accuracy of the maximum restoring force by using the simplified and the constant model in the response analysis



(a) Accuracy of the maximum restoring force using the simplified model and the constant model under earthquake records with various PGV



(b) Accuracy of the maximum restoring force using the simplified model

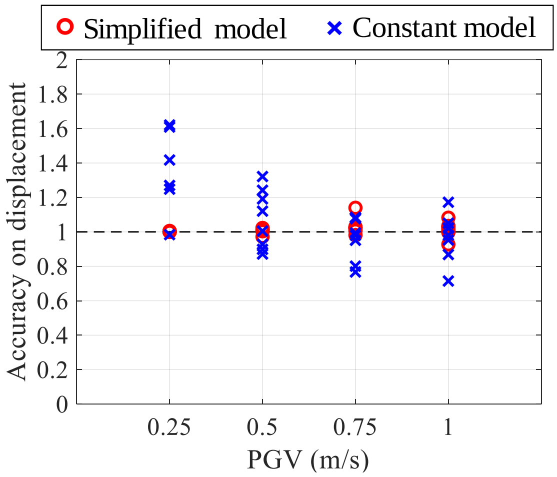


(c) Accuracy of the maximum restoring force using the constant model

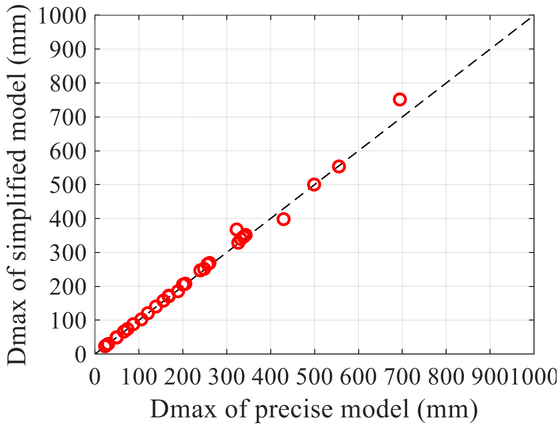
Fig. 3 – Accuracy of the maximum restoring force by using the simplified and the constant model in the response analysis

Fig. 3 shows the accuracy of the maximum restoring force by using the simplified and the constant model in the response analysis. It can be seen from Fig. 3 (c) shows that using the constant model will always tend to underestimate the maximum restoring force. It means the value of a constant friction coefficient that is suitable for most situation under unidirectional sinusoidal excitation may has large error when it comes to unidirectional earthquake input. In the other hand, as shown in Fig. 3 (b), the simplified model gives high consistency with the precise model on the maximum total restoring force.

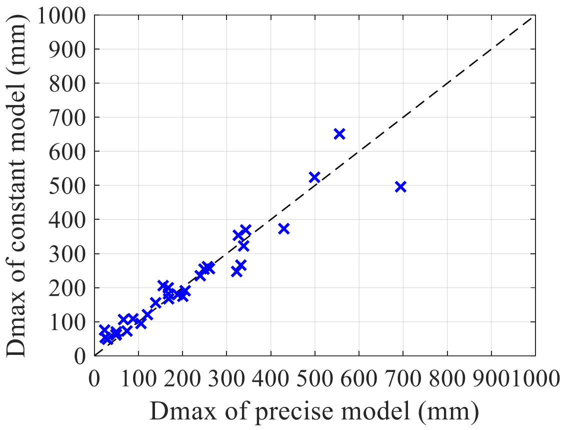
3.2 Accuracy of the maximum displacement by using the simplified and the constant model in the response analysis



(a) Accuracy of the maximum displacement using the simplified model and the constant model under earthquake records with various PGV



(b) Accuracy of the maximum displacement using the simplified model



(c) Accuracy of the maximum displacement using the constant model

Fig. 4 – Accuracy of the maximum displacement by using the simplified and the constant model in the response analysis

Fig. 4 shows the accuracy of the maximum displacement by using the simplified and the constant model in the response analysis. It can be seen from Fig. 4 (a) that when PGV is larger than 0.5 m/s, the constant model will have large chance to underestimate the maximum displacement. Also from Fig. 4 (c), the maximum displacement simulated by the constant model will also tend to be underestimate when the maximum displacement is large. Therefore, it is dangerous to use constant friction coefficient in response analysis even if the value of it has already been validated by tests with unidirectional sinusoidal excitation. The reason of this underestimation is that, when the intensity is large, temperature at the contact surface is high, friction coefficient is small, and, when displacement is large, the velocity is small, the friction coefficient is small. Therefore, the radius of the yield surface, r_f, is small and it will be more difficult to achieve the none sliding status in this kind of situation. As a result, the real r_f will tend to be smaller than the r_f of the response analysis with a constant model and the maximum displacement will tend to be larger. In the other hand, as shown in Fig. 4 (b), the simplified model also gives high consistency with the precise model on the maximum displacement. Therefore, the simplified model is considered to be able to simulate the behavior of the DCFPB under unidirectional earthquake excitation.

3.3 Accuracy of the analysis by using the simplified and constant model under JKB earthquake

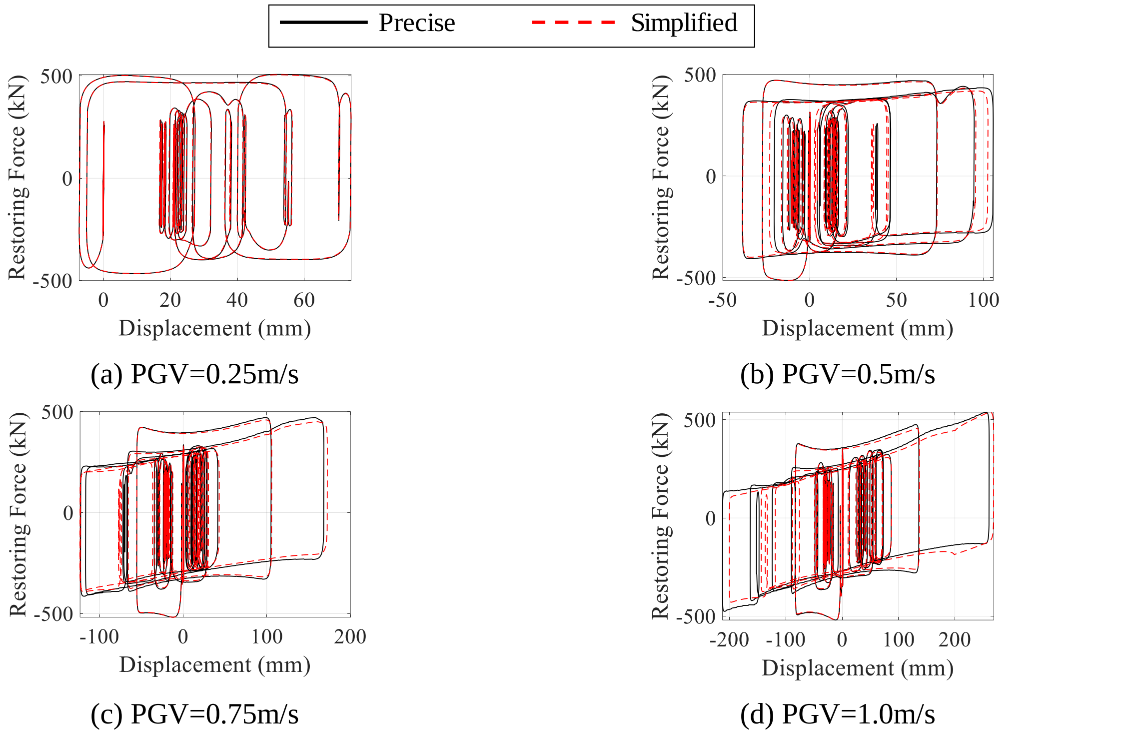


Fig. 5 – Restoring force – displacement curve of response analysis based on the simplified model and the precise model under JKB earthquake

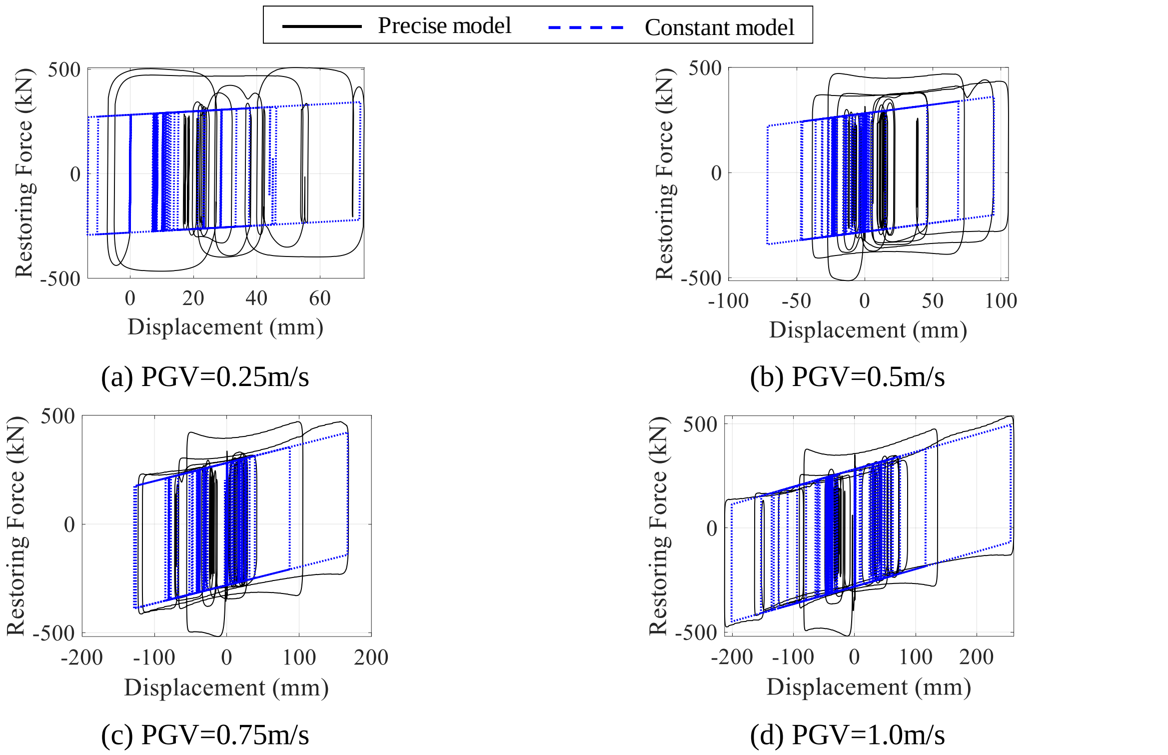


Fig. 6 – Restoring force – displacement curve of response analysis based on the constant model and the precise model under JKB earthquake

Fig. 5 shows the restoring force – displacement curve of the response analysis based on the simplified model and the precise model under JKB earthquake with different peak ground velocity as one of the detailed example of Fig. 3 and 4. This figure is aimed to exhibit the detail of the restoring force and displacement difference between the simplified model and the precise model. It can be seen that not only the maximum restoring force and the maximum displacement, but also the restoring force history and the displacement history of the response analysis results using the simplified model have high consistency with the response analysis results using the precise model.

A detailed example on the restoring force – displacement curve of the response analysis based on the constant model and the precise model under JKB earthquake with different peak ground velocity is also given as shown in Fig. 6. It can be seen that both the restoring force and the displacement of the response analysis results using the constant model have large difference with the results of using the precise model.

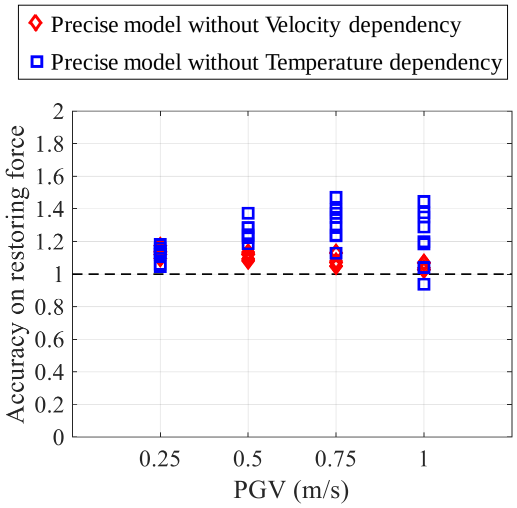
4. Influence of the velocity and temperature dependency on the response analysis

In previous studies, the response analysis of structures isolated with DCFPBs commonly used friction coefficient that only depends on velocity or even constant friction coefficient. However, the value of friction coefficient is also highly related to pressure and temperature. Also, in some cases of experimental design and seismic isolation system design, because of the limitation of testing machines or finance, it is important for designers to know whether certain dependency of friction can be ignored and if it is ignored, how much will be the influence. Therefore, another purpose of this study is to clarify the influence of pressure, velocity and temperature dependency on the seismic response of DCFPBs installed beneath isolated structures. A parametric study was held on the unidirectional response analysis using the precise model in order to investigate the influence of the velocity and temperature dependency on the behavior of DCFPBs under earthquakes.

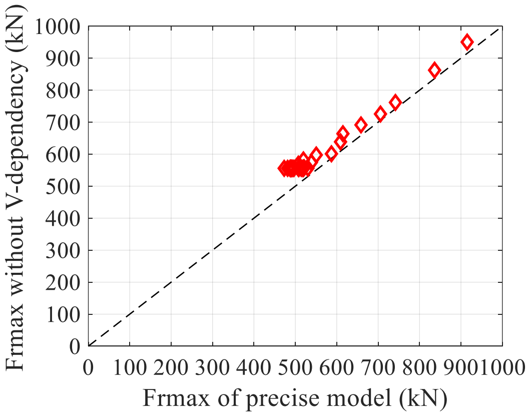
4.1 Influence of the velocity and temperature dependency on the maximum restoring force

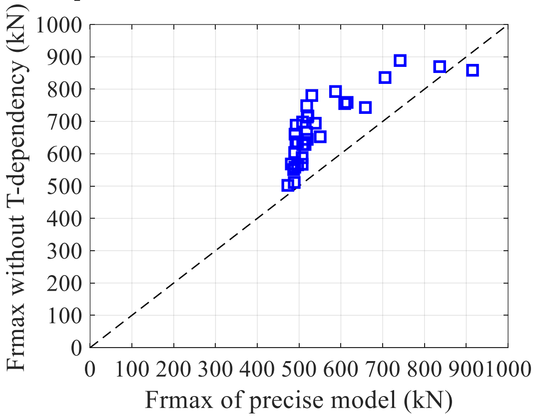
In order to consider the influence of velocity dependency, the velocity dependency factor in the response analysis program using the precise model is taken as '1' throughout the analysis and the analysis results are compared with the original ones. In the same way, when investigating the influence of temperature dependency, the temperature dependency factor will be set as '1'.

Fig. 7 shows the accuracy of the maximum restoring force using the precise model without velocity dependency and that without temperature dependency under earthquake records with various PGV. It can be seen from Fig. 7 (c) that if the temperature dependency is not considered, there is a high possibility that the analysis results will obviously overestimate the maximum restoring force under any earthquake intensity. On the other hand, as shown in Fig. 7 (b), if the velocity dependency is not considered, even though the analysis results will also tend to overestimate the maximum restoring force, the error is relatively small.



(a) Accuracy of the maximum restoring force using the precise model without velocity dependency and that without temperature dependency under earthquake records with various PGV





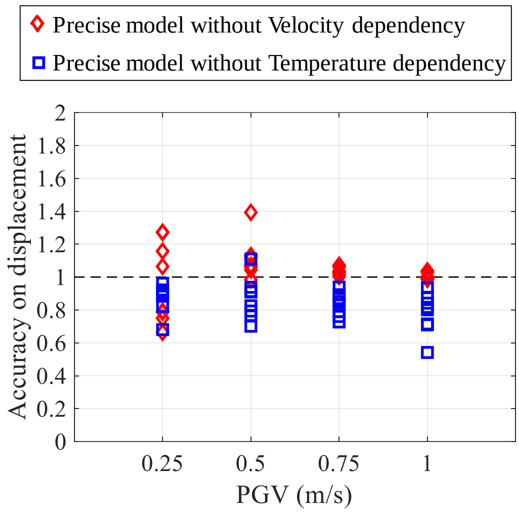
(b) Accuracy of the maximum restoring force using precise model without velocity dependency

(c) Accuracy of the maximum restoring force using precise model without temperature dependency

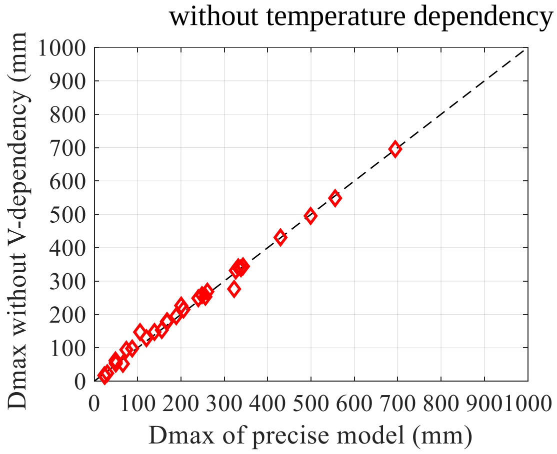
Fig. 7 – Influence of velocity and temperature dependency on the maximum restoring force

4.2 Influence of the velocity and temperature dependency on the maximum displacement

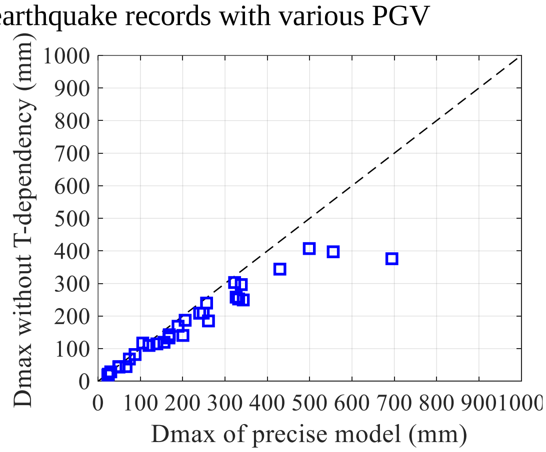
Fig. 8 shows the accuracy of the maximum displacement using the precise model without velocity dependency and that without temperature dependency under earthquake records with various PGV. It can be seen from Fig. 8 (a) that, for DCFPBs installed in isolated structures, if the temperature dependency is not considered, there is a huge chance that the maximum response displacement of the DCFPBs under earthquakes is underestimate. Furthermore, from Fig. 8 (c), it can be seen that, when the maximum displacement becomes larger, the value of the underestimation on maximum response displacement will also be larger. As a result, it is very dangerous to ignore the temperature dependency in the seismic isolation system design. When the velocity dependency is ignored, Fig. 8 (a) shows that the accuracy on the maximum response displacement will be low when PGV is lower than 0.5 m/s. However, Fig. 8 (b) shows that the velocity dependency does not have serious influence on the behavior of DCFPBs especially when the maximum response displacement is large.



(a) Accuracy of the maximum displacement using the precise model without velocity dependency and that without temperature dependency under earthquake records with various PGV



(b) Accuracy of the maximum displacement using precise model without velocity dependency

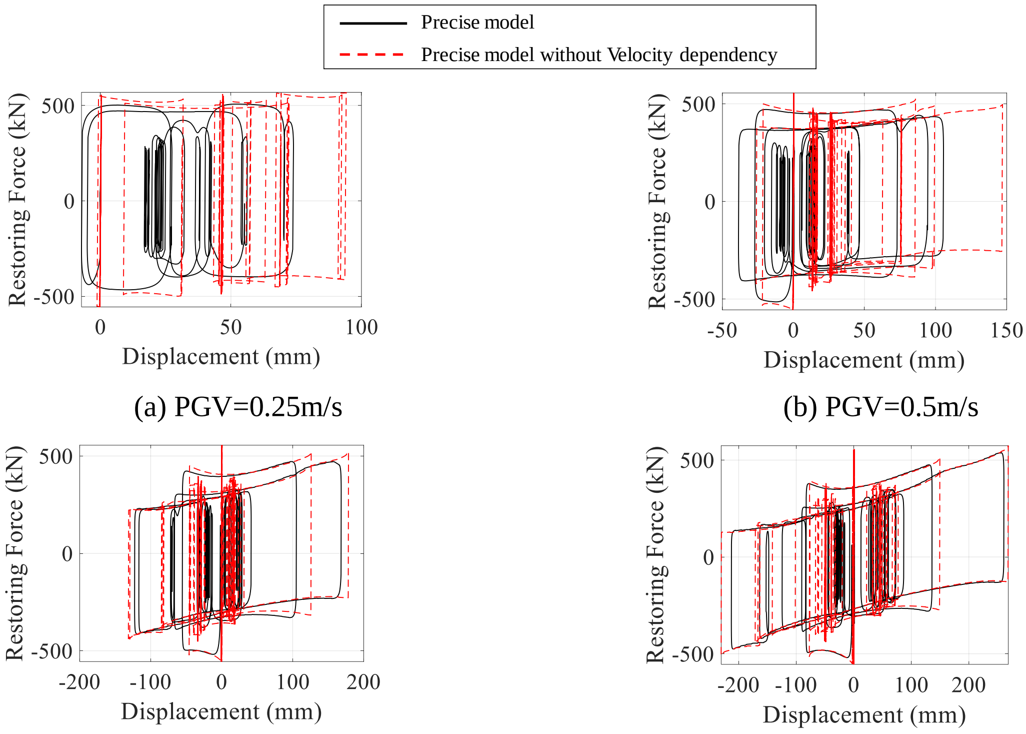


(c) Accuracy of the displacement using precise model without temperature dependency

Fig. 8 – Influence of velocity and temperature dependency on the maximum displacement

4.3 Influence of velocity and temperature dependency on the accuracy of the precise model under JKB earthquake

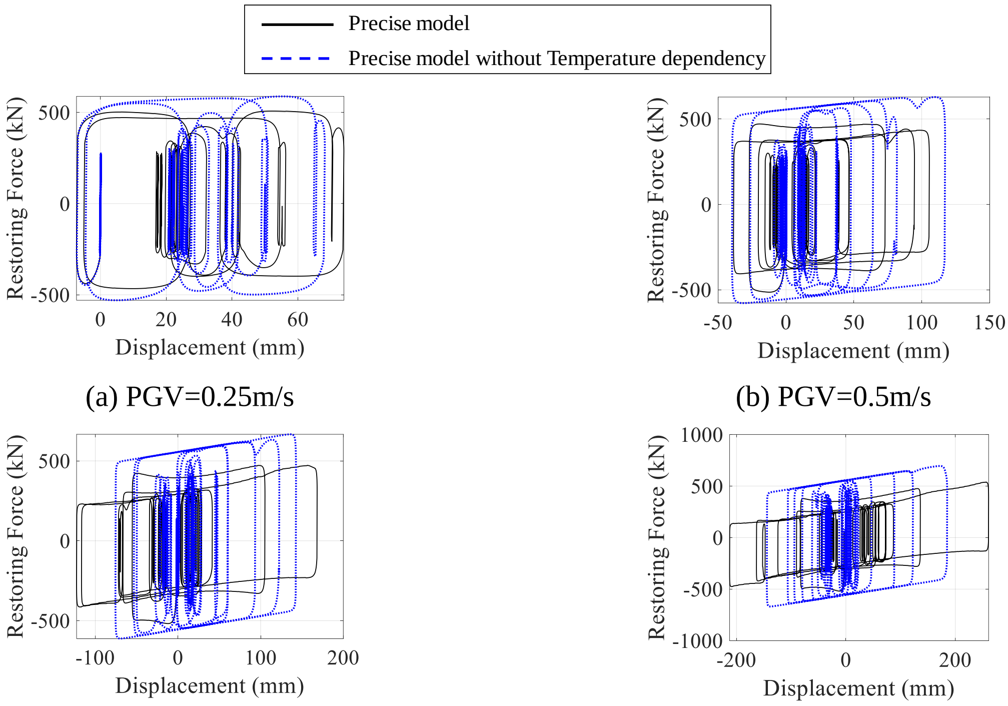
Fig. 9 shows the restoring force – displacement curve of the response analysis with the precise model without velocity dependency and that with the precise model under JKB earthquake with different peak ground velocity as one of the detailed example of Fig. 7 and 8. This figure is aimed to exhibit the detail of the restoring force and displacement difference between the precise model without velocity dependency and the precise model. It can be seen that the larger the PGV, the smaller the influence of velocity dependency, especially on the response displacement. It can also be seen that the error caused by ignoring the velocity dependency mainly occurs at the turning points of displacement, where velocity is relatively small. This is because the velocity dependency factor has larger changing rate at small velocities.



(a) PGV=0.25m/s (b) PGV=0.5m/s

(c) PGV=0.75m/s (d) PGV=1.0m/s

Fig. 9 – Restoring force – displacement curve of the response analysis with the precise model without velocity dependency and that with the precise model under JKB earthquake



(a) PGV=0.25m/s (b) PGV=0.5m/s

(c) PGV=0.75m/s (d) PGV=1.0m/s

Fig. 10 – Restoring force – displacement curve of the response analysis with the Precise model without temperature dependency and that with the precise model under JKB earthquake

A detailed example on the restoring force – displacement curve of the response analysis with the precise model without velocity dependency and that with the precise model under JKB earthquake with different peak ground velocity is also given as shown in Fig. 10. Fig. 10 (c) and (d) show the overestimation of restoring force and the underestimation of displacement if the temperature dependency is ignored in case of JKB record. When PGV equals 1.0 m/s, the maximum response displacement of the analysis result using the precise model is 261 mm, however, the analysis result using the precise model without temperature dependency is 185 mm. If the temperature dependency is ignored in the seismic isolation design and 185 mm is considered as the maximum displacement, it will be very dangerous.

5. Summary and conclusions

Unidirectional response analyses of a rigid-body structure with DCFPBs were conducted using the three friction models. 8 earthquake records with various peak ground velocity, duration time and field distance were selected and they were scaled to records with peak ground velocity equals 0.25m/s, 0.50m/s, 0.75m/s and 1.00m/s as the inputs of the response analysis. The accuracy of the simplified model and the constant model on the response analysis was validated by comparing with the analysis results of the precise model. The result shows that the simplified model can give reliable simulation, while the constant model will tend to underestimate the maximum displacement of the bearing when the peak ground velocity of the input earthquake is larger than 0.5m/s, which is very dangerous for the seismic isolation design.

Parametric studies were also held on the unidirectional response analysis using the precise model to investigate the influence of the velocity and temperature dependency on the behavior of DCFPB and upper structures under earthquakes. The result indicates that if the temperature dependency is neglected, large error in displacement or restoring force simulation may occur. For instance, there will be a high possibility that the maximum displacement of the bearing is underestimated, which is very dangerous for the seismic isolation design. If the velocity dependency is not considered in the response analysis, obvious error will occur under small earthquake intensity, however, the difference on the behavior of DCFPB under large earthquake intensity is small.

In future works, the responses of structures with DCFPBs under real wind loads will be studied. Additionally, vertical earthquake component will be considered in the response analysis and the effect of pressure dependency on the response of the structures will be evaluated. Afterward, the research is expected to move forward to bidirectional and tri-directional responses. Experiments under bidirectional dynamic and earthquake excitation will be conducted, and the performance and applicability of the three friction models, as well as response analysis and the effect of different dependencies, will be further discussed.

6. References

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