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BRIDGE FALLING PREVENTION OF A PRESTRESSED CONCRETE VIADUCT UNDER EARTHQUAKES

Alfinna Mahya UMMATI [1,3,*], Chung-Yue WANG [2]

Abstract: *General Functional Bearing Model (GFBM) is an idea to determine the rubber bearing dissipation capability by analysing the pure deformation capacity and rigid body motions as the two independent mechanisms. Hence, the suitable rubber bearing type can be chosen correctly by the deformation capacity, and the sliding bearing possibility can be accommodated by designing an enough seating size for the elastomeric bearing to prevent the bridge from falling. GFBM was inspired by the actual case of some bridges in Taiwan where the rubber bearing placed in between the deck and column-cap without anchor bolts as the concept of the fusing bearing on IDOT. A prestressed concrete viaduct located along the highway in the middle region of Taiwan was indicated to be over-deflected and suffer from cracks. Then, rubber bearings were installed to sustain the maximum deflection without anchored either to the deck or additional column. A GFBM analysis was conducted to estimate the seating size of this additional bearing and column, and also to examine the other rubber bearings conditions. The bridge was modelled as a 3D frame element that initiated by the benchmark analysis to validate GFBM within numerical analysis and experimental test result, then, GFBM applied to the complex structure to evaluate a pre-stressed concrete (PSC) viaduct under two destructive earthquakes in Taiwan, 2022 Taitung and 1999 Chi-Chi Earthquakes. This research proposed the application of GFBM analysis for bridge assessment to prevent from superstructure falling under the earthquakes related to the experimental test and numerical simulation.*

Introduction

As a country with high seismic intensity, Taiwan continuously develop much technology in construction so that the concept of a resilient structures made them survive during the earthquakes, for example is the use of seismic isolator. Seismic isolator believed it can reduce the structural drift and acceleration, rubber bearing is one of the devices which apply the concept of seismic isolator by providing low lateral stiffness yet high in vertical stiffness. Hence, when the structure hit by an earthquake, the shear force which transferred from the column to the deck can be reduced by converting it become the bearing deformation and sliding motion. Then, it is important to consider the elastic deformation of the rubber bearing and the possibility of sliding to keep the bearing remain in seat. Regarded to the research that conducted by Kawashima and Unjoh, (1997), the bridge failure during the Great Hanshin Earthquake in 1995 majorly reported due to the bearing failure such as the bearing large deformation which caused in losing the anchor bolts or the stopper, dislocation of the decks after the bearing failure would impact the huge lateral shear force and induced the failure to either their own and adjacent columns as the domino effect, hence it was preferable to consider about the rubber bearing with allowable movement to endure the lateral shear force. Liu and Chang, (2006), mentioned that during the Chi-Chi Earthquake that impact Taiwan in 1999, the bridge failure also dominated by the superstructure movement and the sliding bearing failure which caused decks collision in the expansion join separation, a study to define a proper retainers or shear key as the unseating prevention device was proposed in order to limit the excessive sliding. The same idea, the Earthquake Resisting System (ERS) by Illinois Department of Transportation (IDOT) mentioned that the bearings preferred to design as the quasi-isolation system where the bearings is permitted to have allowable failure, hence, the sufficient seat must be provided and the limited sliding movement is permitted as long as the deck remain in safe, Filipov et al., (2013). China also become one of the countries that adopting the typical idea, rubber bearing is widely used in China and most of them are installed by put the bearing directly seated to the column cap without any anchor bolts either to the column or girders. Releasing the connectivity of the rubber bearing on its both sides is not in line with the common

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[1] Ph.D. Candidate, National Central University, Taoyuan, Taiwan, alfinnamahya@g.ncu.edu.tw
[2] Professor, National Central University, Taoyuan, Taiwan
[3] Researcher, Sumatera Institute of Technology, South Lampung, Indonesia

seismic design code which required the whole bridge structure to be perfectly connected, however within this way, the ultimate shear deformation can be enlarged up to 200% according to Mori et al., (1999) and Li and Wu, (2017), before the rubber bearing was completely failed when it reached 300 - 400% Li and Wu, (2017). It is helpful to exploit the performance of rubber bearing technically with dissipating more energy and improve the bridge capacity during the earthquake by controlling the relative displacement of the intersection between sub- and superstructure.

The sticking and sliding state of the functional bearing system developed to determine the changing state of the unanchored bearing system related to the relationship between the inertial and friction force that changing by the time history when the bearing is one sided anchored, (Liu, Liu and Huang, 2019). General Functional Bearing Model (GFBM) developed the previous functional bearing system in more functionable fixity-free condition which totally unmerge the function of restoring and friction forces when the rubber bearing is totally unanchored to observed the maximum capacity of the rubber bearing and designing the sliding interface parameter to keep the bridge in safe during the earthquakes, Ummati et al., (2022). The rubber bearing may become unstable when the axial load rising together with reducing the lateral stiffness which enhanced the lateral displacement (Sanchez *et al.*, 2013). Releasing the bearing fixation(s) somehow put the bridge in dangerous condition if the design is not well-estimated. GFBM analysis can be used to evaluate the existing bridge to assess the rubber bearing condition as the baseline whether the rubber bearing itself or the seating size need to be replaced or retrofit.

As mentioned before, it is very common to install the rubber bearing as the bridge support without the anchor bolts, thus it can remove anytime easily when its failure, and this technical installation also give more advantage with improving the bridge performance during the earthquake. A prestressed concrete highway bridge (viaduct) located in the middle part of Taiwan put the rubber bearings in that way. This bridge located near the active faults which supposed to be highly impacted by the earthquakes. In the other hand, during 17 years of its service life, this PSC viaduct suspected to have over-deflection, hence, the additional rubber bearing and column is necessary to install to sustain the bridge from the failure. A GFBM analysis conduct to estimate the proper seating size of the additional bearing and evaluate the current seating size of the bearings in the main structure under two destructive earthquakes which ever hit Taiwan in 1999 and 2022.

Benchmark Analysis of GFBM for a Single Span Bridge

Material Properties and Geometry Modelling

A single span bridge made by concrete deck and hollow steel column modelled as 2D frame element using SAP2000 structure analysis software and the analysis was done by modelling the rubber bearing as the conventional model and GFBM, both results will be validated by the experimental test result. The material and section properties listed on Table 1 below:

Property	**B-(cm)**	**H- (cm)**	**D-(cm)**	**L-(cm)**	**E-(KN/cm^2)**
Deck (Concrete)	50	20	-	500	3044
Rubber bearing	Link Element				
Pier-head (Steel)	51	30	-	5	19995
Column (Hollow Steel)	-	-	16.9	60	21118
Footings (Steel)	60	60	-	10	19995

Table 1 Bridge material and geometry section

Where B, H, and D is the width, height, and diameter of the model, L is the length along the axial direction and E is the elastic modulus. The deck supported by the rubber bearing and placed in between the deck and pier-head intersections, the footings fixed to the ground. The rubber bearings of the experimental specimen were perfectly anchored to the deck and pier-head as the conventional model. The rubber bearing modelled as the link element with the horizontal stiffness is 4.8 kN/cm and other specifications are the same with the rubber bearing that used in the experimental test. The finite element modelling of the bridge is shown as in Figure 1.

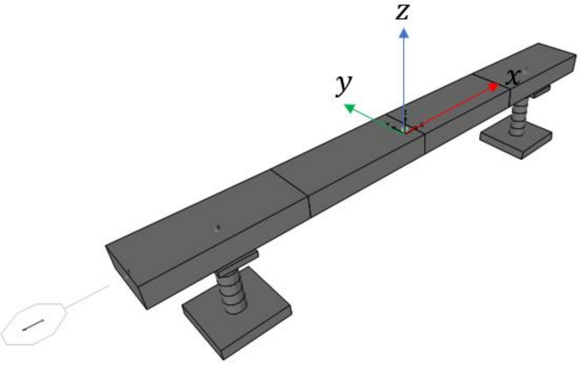
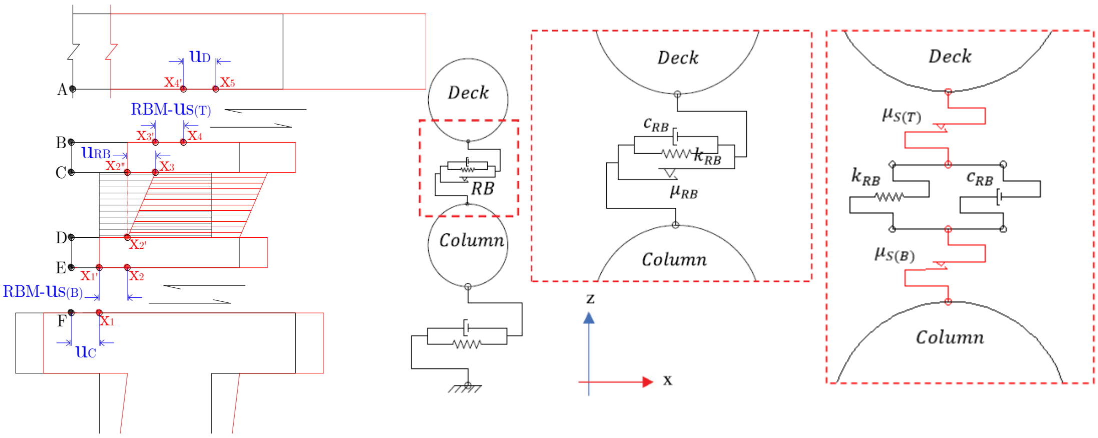


Figure 1 Bridge model.

GFBM explanation and benchmark analysis result

The bridge loaded by the near-and far-fault records of the Chi-Chi and El-Centro Earthquakes, there were 50-gal ground acceleration to represent the low earthquake magnitudes and 450-550 gal for the high earthquake's magnitude. Although it was known that the near fault is highly impactful to the structure than the far-fault earthquakes related to the shocking pattern, but the possibility of the near fault earthquake which also has the far-fault effects also consider.



(a) (b) (c)

Figure 2 (a). Sliding path in a rubber bearing, (b). Conventional model, (c). GFBM.

The rubber bearing as in conventional model assigned as a single rubber bearing link which connected to the same nodes with deck and column as the common ways as in Figure 2(b). Meanwhile, GFBM is the bearing modelling method which assume the interconnection nodes in conventional model as the friction springs with the boundary conditions reflect the friction surface intersection's parameters and/or anchors as in Figure 2(c). Thus, within GFBM analysis, the rubber bearing deformation capability, the sliding motion, or the critical state between sticking and sliding can be detected separately. Rubber bearing processed the transferred earthquake energy become the deformation, when the earthquake energy induced by the inertial force is larger than the friction force, the static friction turned to kinetic friction parameter and the sliding motion happens at the concerned interface. Thus, the role of the friction interface is to receive the excess energy from the rubber bearing, and again, the excess energy from the friction interfaces will processed as the rigid body motion or the sliding bearing translation which caused the bridge falling during the large earthquakes. Within GFBM idea, it is more convenient to design the sliding displacement of the rubber bearing by controlling the rigid body motion on the bearing interfaces. It can be seen on Figure 3 of the conventional model hysteretic loop of the rubber bearing under the earthquake, the sliding detected to the rubber bearing as S1 and S2 instead of the deformation loop L1, L2, and L3. However, the sliding motions and rubber deformations are mixed up and it is not easy to identify each contribution separately and will not happen If the rubber bearing and interfaces element unmerge into several links elements as resulted in Figure 4.

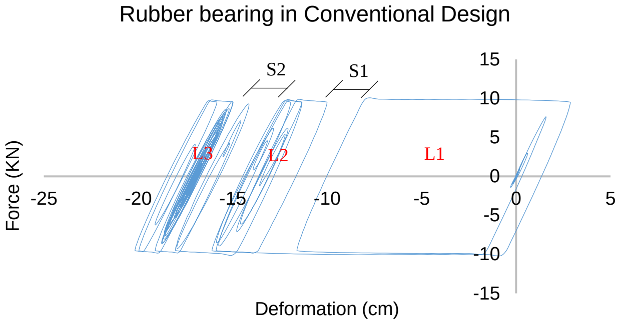


Figure 3 Rubber bearing link hysteretic loop using conventional design

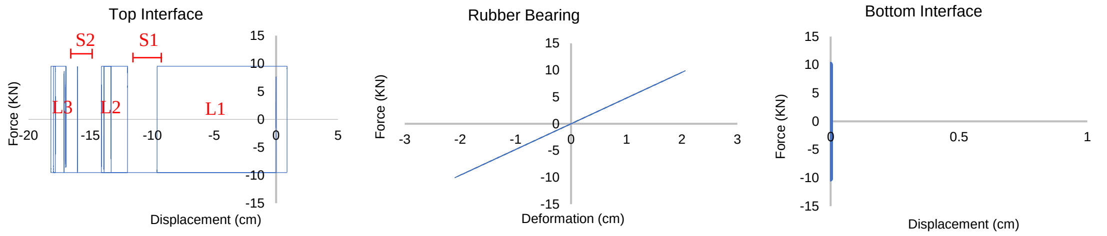


Figure 4 Hysteretic loop of each element using GFBM analysis.

Figure 3 and Figure 4 use the same rubber bearing parameters, within the GFBM analysis as described before, the rubber bearing maximum deformation capacity can be calculated, yet S1 and S2 are the sliding displacement happens at the top interface and the exact number are clearly identified. Now, each rubber bearing failure possibility can be estimated clearly when the rubber bearing is analysed using GFBM.

The benchmark analysis performed to verify the analysis result of the rubber bearing using GFBM that supposed to be satisfied the conventional model analysis as in common researcher used and the experimental test result. For a single span bridge as in Figure 1, the bridge deck supported by the rubber bearings on both column and loaded by some earthquakes with low-high earthquakes magnitude as explained before. Every method that used to model the rubber bearing supposed to be have the same deck response, thus, the deck acceleration for all those three methods were compared and the acceleration histories plotted on Figure 5.

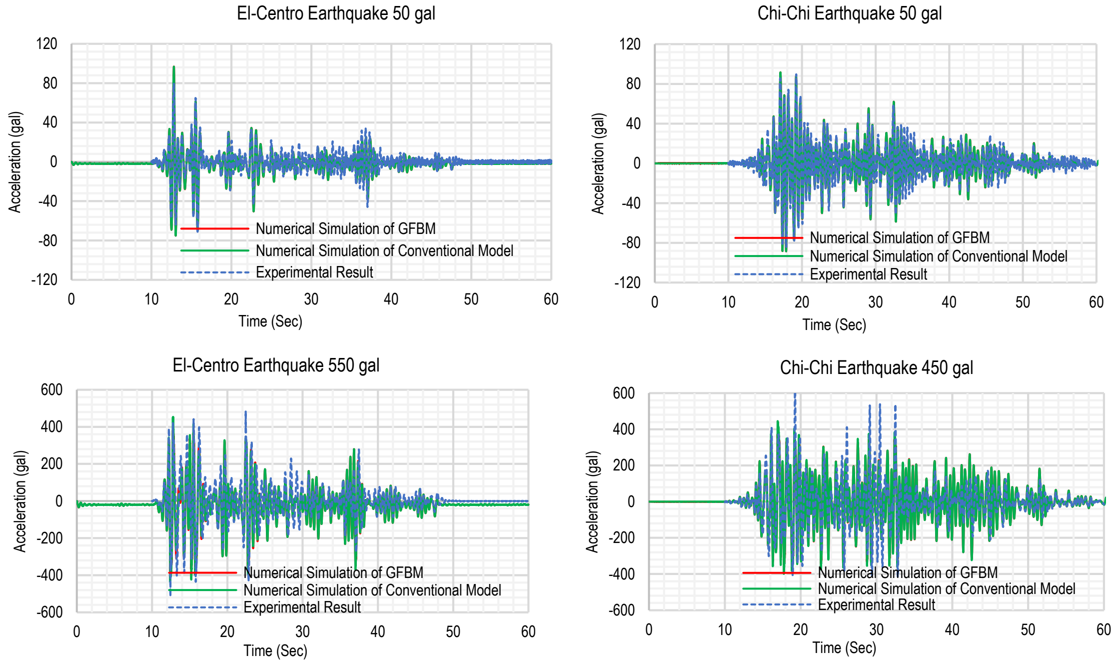


Figure 5 Deck acceleration comparison

The deck acceleration of the single span bridge analysis with three case of rubber bearing was compared and resulted 4% difference averagely with the experimental result. Hence, the rubber bearing within GFBM analysis can reflect the conventional model and the experimental result. However, GFBM analysis are able to provide more information which will be not easy to identify if the rubber bearing analysed using conventional model. Now, the performance of the GFBM for the laboratory scale analysis can be validated and will be used to monitor the sliding surface demand of a prestressed concrete viaduct with the fuse (Unanchored) elastomeric bearing in Taiwan.

GFBM Analysis for a Prestressed Concrete Viaduct

Introduction to the Prestressed Concrete Viaduct with Fuse Elastomeric Bearing

Taiwan highway system are commonly made by the prestressed concrete segmental bridge construction. This highway bridge or viaduct was open for traffic since 2004 and some part detected to suffer with cracks and over-deflection. The structure dominantly made by the concrete structure with the compressive strength was 484 kgf/m^2, elastic modulus was 30.44 GPa, and poison ratio was 0.2. The deck made as the segmental prestressed girder with seven wire strand of internal tendon reinforcement with the initial jacking stress was 365 tonf and 15.2 mm of the tendon's diameter which spread in top and bottom part of the girders. The overview of the bridge modelling is on Figure 6 below:

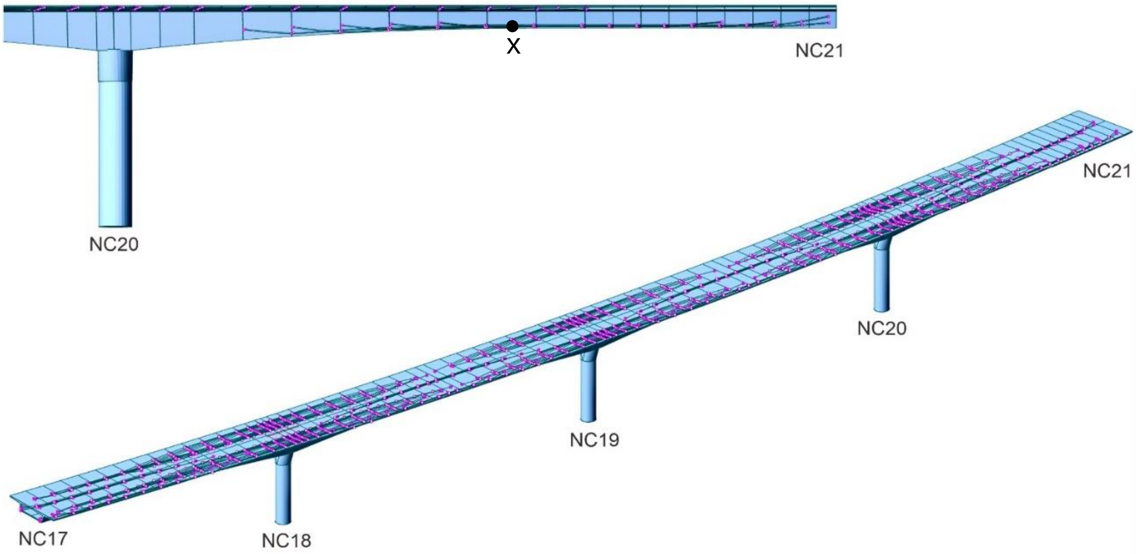


Figure 6 Prestressed concrete viaduct numerical model

The driving discomfort as the result of the bridge sagging was reported on 2008 and it was found by the surveying that the bridge was deflect up to -20 cm of span NC20-NC21. Deflection monitoring project started with installing several inclinometers along this span to monitor the deflection development from 2010-2020. Since the viaduct constructed as the continuous span, NC17-NC21 need to build in numerical modelling to get an accurate analysis result of span NC20-NC21 using Midas Civil commercial software. FDOT (2022), define the tensile stress limit of the segmental bridges as the eq. (1) below:

$$\bar{\sigma}_t = 3.5\sqrt{f'c(psi)} \qquad (1)$$

related to the current compressive strength, the tensile stress is equal to 204.17 tonf/m^2 and the cracks happens if the principal stress in tension is larger than the tensile stress limit. Figure 7 shows the stress analysis development of NC17-NC21 sections during the service life and the cracks proved by stresses in some part excess the stress limit which getting higher during the time.

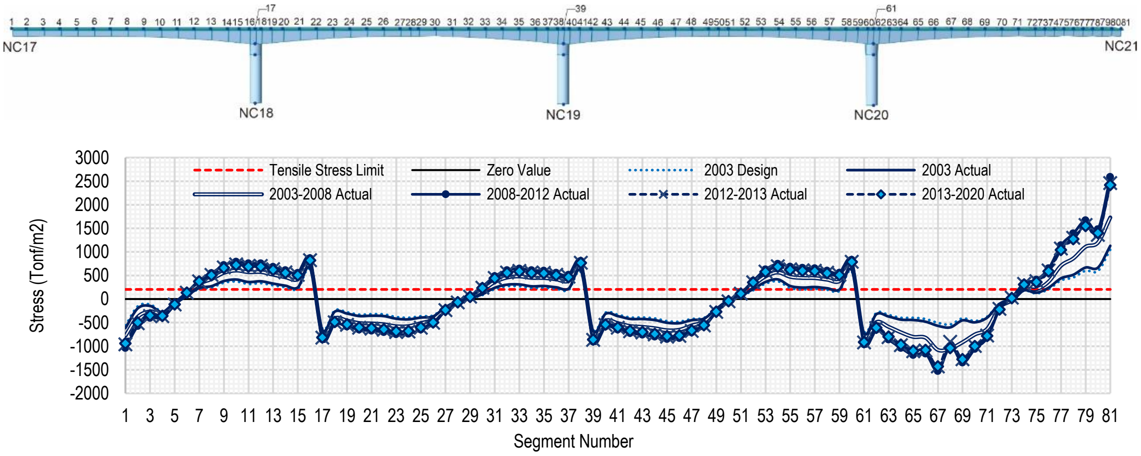


Figure 7 Stress analysis of NC17-NC21

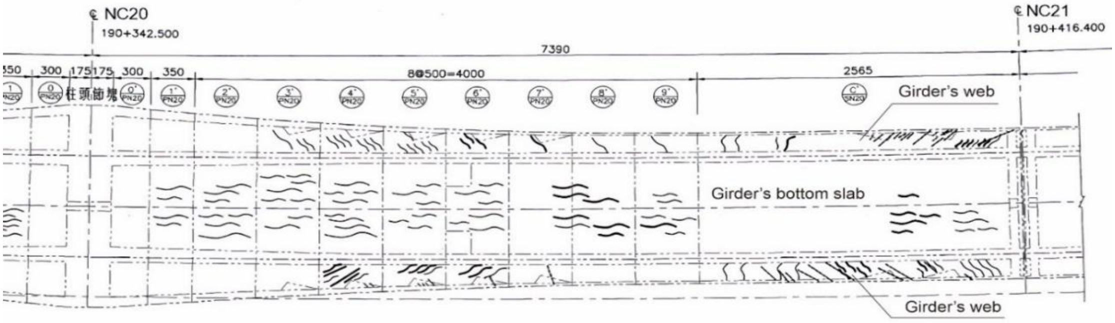


Figure 8 Cracks identification of NC20-NC21 in 2020

The first retrofitting of NC20-NC21 was done by installing some external tendon in 2009 to mitigate the instance deflection which may occur, however, as the part of the bridge maintenance, several pavements works performed for the vehicle safety reason. Hence, in the end of 2020 the bridge deflected up to -25.39 cm and estimated to be continuously increased with the current cracks' identifications from inside the bottom girders as in Figure 8. The additional column was installed in the maximum deflection location to overcome the further damage with the rubber bearing designed not to anchored either to deck or the pier head as the fuse elastomeric bearing to let the deck movement. Instead of the elastomeric bearing in this additional column, the fuse bearing also applied to the bearing support of the main bridge, specifically on NC17 and NC21. Now, the GFBM is used to estimate the sliding accommodation of the fuse elastomeric bearing of the additional column and observe the current pier head is capable to accommodate the sliding bearing related to the current and designed destructive earthquakes.

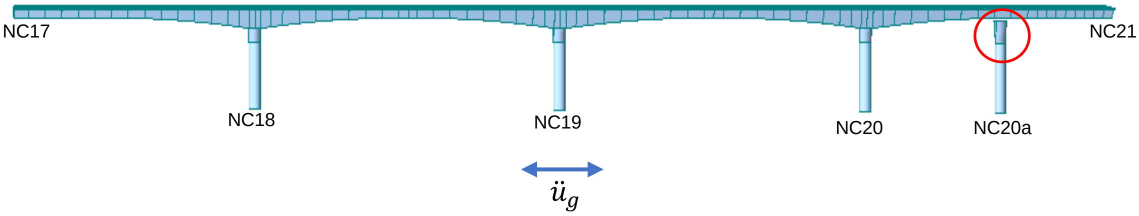


Figure 9 Additional column marked by NC20a

Figure 10 The unanchored bearing of NC20a

Earthquakes

In the middle of September 2022, south-eastern part of Taiwan hit by a couple of 2022 Taitung Earthquakes with 6.4 and 6.8 magnitude according to the MMI scale, which the aftershock happened in a day after, it was remained all the researchers from the devastating earthquake which happen on 1999 of Chi-Chi Earthquakes. Baohua Bridge, Luntian Bridge, Changfu Bridge, and Gaoliao Bridge were several damaged bridges which mostly caused by the large displacement of the superstructures, NCREE (2022). However, the similar evidence of all those bridges were the piers that perfectly fine which emphasize that the collapsed dominantly because of the superstructure movement which is not easy to predict by the conventional model.

The NC17-NC21 bridge assessment was done by observed the bridge under 2022 Taitung Earthquake and 1999 Chi-Chi Earthquake both earthquake sources located on Taitung City and Nantou County. The bridge that observed located on Taichung City, design spectra analysis is necessary due to the earthquakes loading and the bridge located in different locations. The step to normalize the input ground motions are as follows: 1. The response spectrum generated from the original ground motions history were plotted, 2. The graph of spectral acceleration (SA) design of Taichung city were generated from the official website of Taiwan government, 3. Identify the structural period, 4. Compare the spectral analysis design from step 2 with the response spectrum of the original ground motion from step 1, 5. Use the structural period to mark the related spectral acceleration of the original response spectrums, 6. The original time history acceleration multiplied by the scaling factor which calculated by the ratio of spectral acceleration of the design spectra of the bridge location and the original earthquake, Ummati and Wisnumurti, (2018). The normalized ground motions that used as the bridge loading plotted on the Figure 11 which positioned on the ground as $\ddot{u}_g$ in Figure 9.

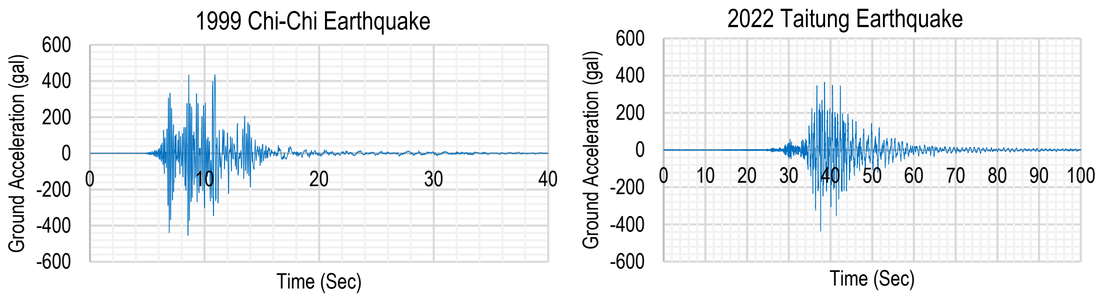


Figure 11 (Left) 1999 Chi-Chi Earthquake 454 gal, (Right) 2022 Taitung Earthquake 437 gal

Sliding Accommodations of a Fuse Elastomeric Bearing

The additional column installed as in the Figure 9 located at the maximum deflection location of span NC20-NC21 for the mitigating action based on the last deflection record which shown -25.36 cm in the end of 2020 by field monitoring. The elastomeric bearing directly placed above the additional column as in Figure 10, prevent the sliding under low-magnitude of earthquake by adjusting the material friction by rubber-steel and rubber-concrete for the top and bottom interfaces, then let the sliding happen under the large magnitude earthquake as the concept of fuse elastomeric bearing, Filipov et al., (2011, 2013). Based on the study of frictional force to identify the friction coefficient between the rubber and another material, the friction coefficient of the rubber bearing and concrete is 0.49 Zhou et al., (2021), however, for the rubber bearing and steel is 0.35 Xiang and Li, (2017). The bearing component of NC17-NC21 is the unanchored rubber bearing with the rubber-concrete for the top and bottom interface. There are two phases of the bearing in its response under the earthquake. First, the bearing deformed elastically under the low magnitude, in this state, the static friction condition happens when the rubber is not possible to bear more deformation. Once the excitation is higher than the static friction force, the static turn to be kinetic friction force and the sliding happens in phase of sliding state. The rubber bearings placed on the concrete blocks above the pier-head, designed with 5 cm of the seating size in four sides of the bottom interface.

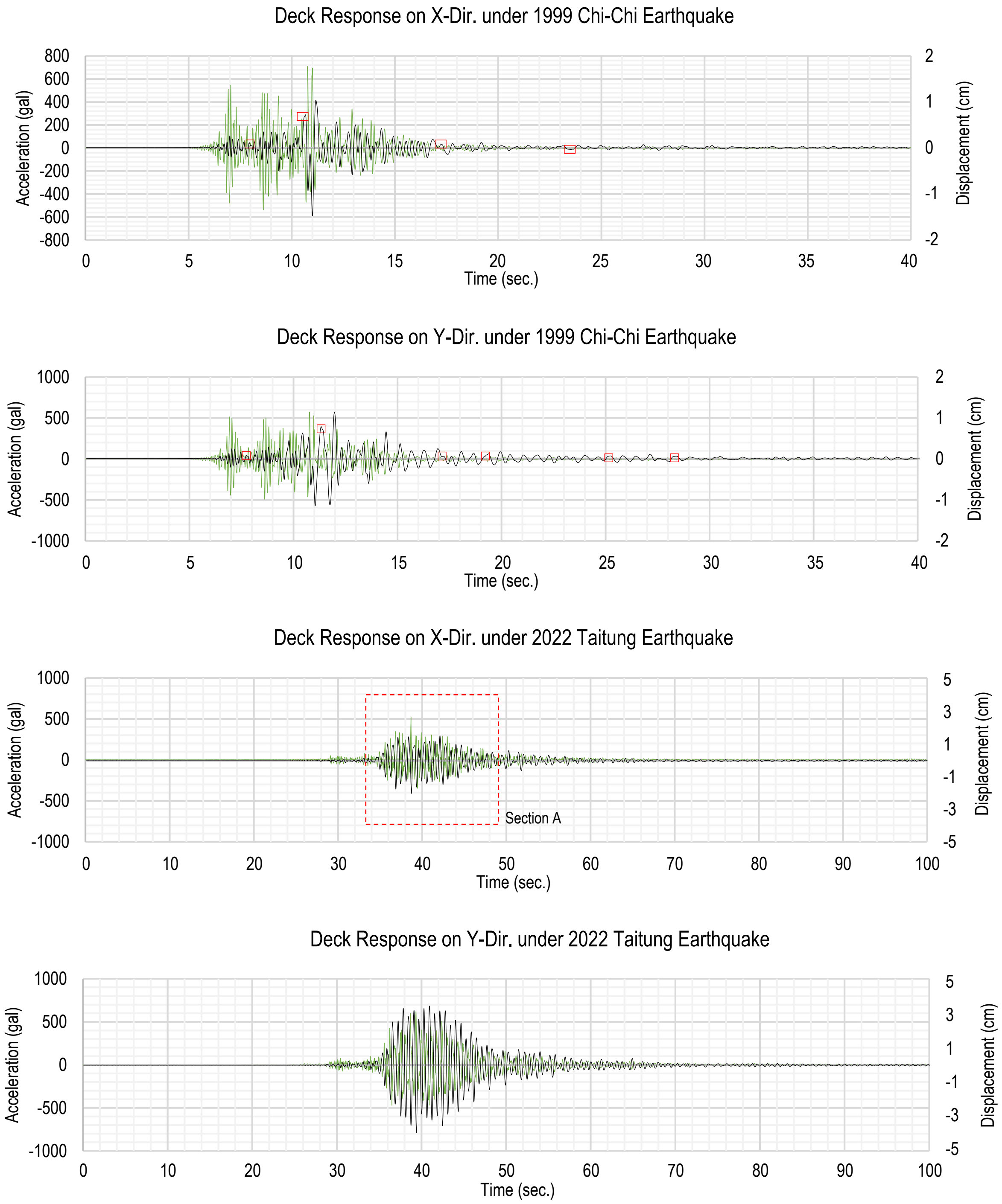


Figure 12 Comparison of the deck acceleration (green) and displacement (black)

The deck response observed on segment number 81 (see Figure 7 (Top)) related to the displacement and acceleration at that point as in Figure 12 under the earthquakes, where direction X is along the bridge span direction and Y is along the cross-section direction. The role of modelling the rubber bearing as in GFBM or fusing bearing ease the designer to observed the bearing displacement as marked by the red line on Figure 13 of the sample displacement history which captured by section A of the deck response in X-direction under 2022 Taitung Earthquake on Figure 12, these signs shows the deck which swayed due to the rigid body motions happen on the rubber bearing interfaces.

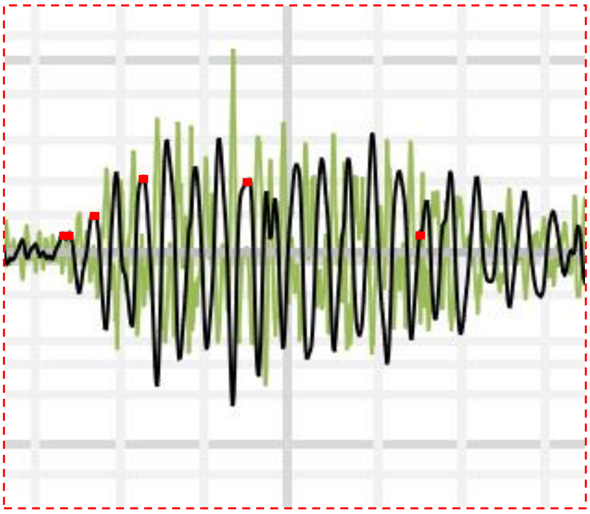


Figure 13 Section A of figure 11 shows the deck displacement which reflect the bearing displacement

As mentioned before, the elastomeric bearing of NC17-NC21 were installed by the concept of fusing bearing which allowed the bearing to deform then displaced at the limited distance under the large magnitude, the numerical modelling performed and modelled the elastomeric bearing as the GFBM as mentioned before by applying the elastic link to represent the rubber bearing which series-connected by the friction springs to represent the top and bottom bearing's interfaces. According to both destructive earthquakes, 1999 Chi-Chi Earthquake and 2022 Taitung earthquake, which hit Taiwan and caused some serious damage, these two earthquakes were normalized then used as the bridge excitation and resulted the rubber bearing deformation and interfaces movement as in Table 2.

1999 Chi-Chi Earthquake						
Bearing Location	NC17		NC20a		NC21	
Direction	Dx	Dy	Dx	Dy	Dx	Dy
Top Interface (cm)	-0.983	0.523	-0.052	0.003	0.895	0.577
Rubber Bearing (cm)	-0.001	0.001	0	0	0.001	0.001
Bottom Interface (cm)	-0.983	0.523	-0.052	0.003	0.895	0.577
2022 Taitung Earthquake						
Bearing Location	NC17		NC20a		NC21	
Direction	Dx	Dy	Dx	Dy	Dx	Dy
Top Interface (cm)	0.864	1.585	0.095	0.004	-0.944	2.023
Rubber Bearing (cm)	0.001	0.002	0	0	-0.001	0.002
Bottom Interface (cm)	0.864	1.585	0.095	0.004	-0.944	2.023

Location of NC17, NC20a, and NC21 described on Figure 9

Table 2 Rubber bearing deformation and sliding displacement estimation

Conclusion

The numerical analysis performed to validate the spring model to represent the fusing bearing configuration of NC17-NC21 by modelling the rubber bearing and friction interfaces as an elastic restoring spring and friction springs separately to identify the rubber bearing pure deformation and rigid body motion within the concept of General Functional Bearing Model (GFBM) analysis which represent the actual case of experimental test. Then within an accurate bridge model approximation, GFBM Bridge was used to estimate the rubber bearing and sliding behaviour of NC17-NC21 under 1999 Chi-Chi Earthquake and 2022 Taitung Earthquake that were two earthquakes which hit Taiwan destructively. The unanchored rubber bearing placed above the piers which accommodated by 5 cm gap to allow the bearing to slide. The numerical analysis estimated that under 1999 Chi-Chi Earthquake 454 gal, the maximum sliding bearing occur on the bearing placed on pier NC17 with 0.983 cm at the same time the rubber deformed 0.001 cm. In the other hand, under 2022 Taitung Earthquake 437 gal, the maximum response occurs on the bearing which placed on pier NC21 with 2.023 cm translation.

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