EFFECT OF POUNDING ON THE SEISMIC PERFORMANCE OF CONTINUOUS BRIDGES

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ABSTRACT :

This paper represents an analysis of a 3-span simply supported bridge considering the effect of failure of elastomeric bearings. It is known from the analysis that elastomeric bearings and restrainers start to fail or yield progressively from edges due to rotation of the decks. It is also shown that design concept to evaluate the seismic demands of bearings and restrainers by dividing the total seismic demand by number of devices underestimates real seismic demands at the edges of girders due to combined rotation and translation of the deck during excitation.

KEYWORDS: bridges, seismic response, pounding, bearings, restrainers, progressive failure

1. INTRODUCTION

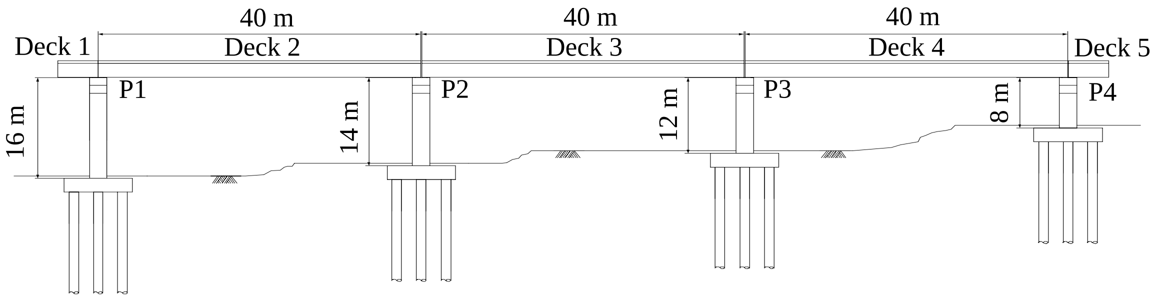
Poundings which occur between decks significantly affect the seismic response of bridges. Large impact forces which are generated by collisions are transferred to the adjacent decks, and this can result in progressive failure of the bearings and columns as well as restrainers. Failure of a bearing or a restrainer can increase the seismic lateral force in the rest of bearings and restrainers, and this can result in failure in the bearings and restrainers. Consequently failure interaction among main structural components is important in the evaluation of possible collapse modes.

This paper presents an analysis on the progressive failure of bearings of a 3-span simply supported bridge. Effect of failure of bearings on the total bridge response including residual drift after the excitation is analyzed including collisions between decks.

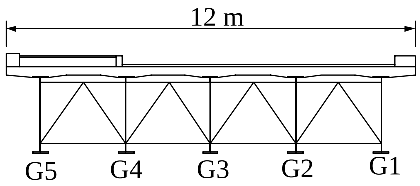
2. TARGET BRIDGE AND ANALYTICAL MODELING

A 3-span simply supported steel plate girder bridge as shown in Figure 1 is analyzed here. A superstructure consists of a deck and 5 steel girders (G1-G5). Each deck is 40 m long and the gap between the decks is 100 mm. Decks with a weight of 6.53 MN each are supported by 8-16 m tall cantilevered RC piers (P1-P4) resting on pile foundations. Decks are supported by 96 mm tall and 440 mm wide square natural rubber elastomeric bearings. It is assumed in analysis that the bearings rupture when shear strain of the bearings during excitation reaches the ultimate shear strain of 250 %, which corresponds to the design shear strain of elastomeric bearings based on the 2002 Design Specifications of Highway Bridges, Japan Road Association. Once the bearings rupture, restoring force of the bearings is assumed to become zero. PC cable restrainers are accommodated between the I-girders.

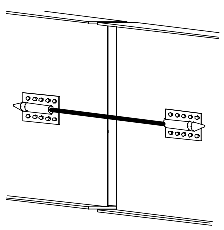
In analysis, the decks are idealized by 3-D linear beam elements. The strut action of the RC slab is idealized by grids of the elements as shown in Figure 2. Decks 1 and 5 which exist next to the bridge is approximately taken into account in analysis by lumping a half of the deck mass at the top of P1 and P4, respectively. The plastic hinge region of the piers are idealized by fiber elements using constitutive models of confined concrete and reinforcements [Hoshikuma et al. 1997, Sakai and Kawashima 2006]. Poundings which occur between the adjacent decks are idealized by the impact springs [Watanabe and Kawashima 2004]. Once a bearing suffers extensive damage, there is an extreme occasion that failed portion or components constrain and restrict the



(a) Target bridge



(b) Superstructure



(c) PC cable restrainer

Figure 1 Target Bridge and Restrainers

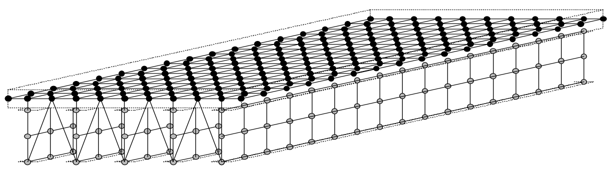
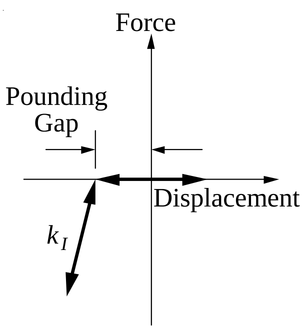
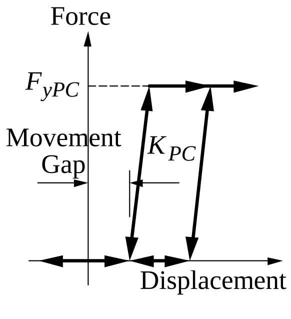


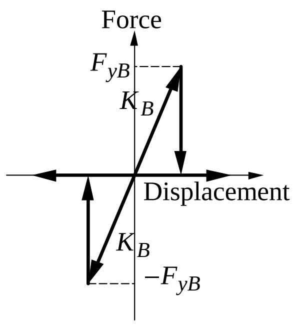
Figure 2 Model of the Deck



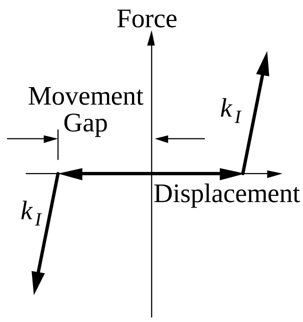
(a) Impact spring



(b) PC cable restrainer



(c) Elastomeric bearing

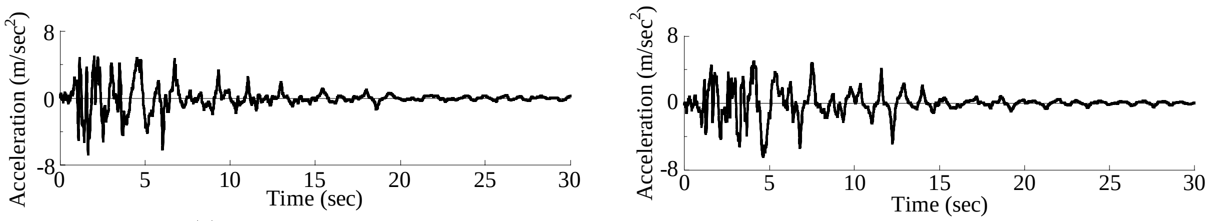


(d) Lock of bearing after failure

Figure 3 Idealization of Pounding, Restrainers, Elastomeric Bearing and Lock of a Bearing after Failure

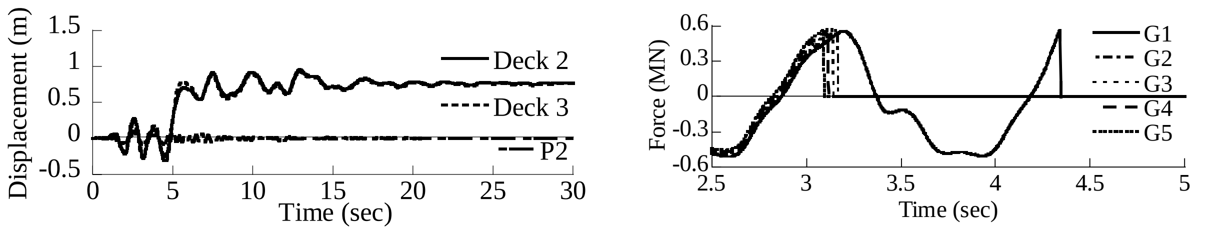
relative displacement of the bearing. For example, rough surface of ruptured bearing increases restriction for bearing movement, and failed components or pealed out steel blocks from failed bearings could prevent bearing movement. Dislodged and settled girders due to failure of bearings cannot easily come back to the original position. Lock of bearings could result in extensive damage of bridges because excessive inertia force is transferred from a deck to the substructures.

Figure 3 shows idealization of pounding by the impact springs, the PC cable restrainers, the elastomeric bearings before and after rupture, and the lock of failed bearings. In the “lock” of a failed bearing, it is assumed that some relative displacement can take place without restriction; however the failed bearing restricts the relative displacement over a threshold movement (movement gap). This corresponds that the relative movement



(a) NS component
(b) EW component

Figure 4 JR Takatori Station Record during 1995 Kobe Earthquake



(a) Response displacement of Deck 2, Deck 3 and P2
(b) Restoring forces of G1-G5 bearings which support Deck 3 on P2

Figure 5 Response Displacement of Deck 2, Deck 3 and P2 in the Longitudinal Direction

of the bearings is restricted over the movement gap. It is assumed here that lock can take place in both the longitudinal and transverse directions. The movement gap is assumed in this analysis as 50 mm in both longitudinal and transverse directions. The stiffness in tension, the strength, the deformation capacity and the gap of a PC cable restrainer are set as 3.48×10^4 kN/mm, 0.574 MN, 16.5 mm and 50 mm, respectively. The strength of an elastomeric bearing is 0.57 MN in both the longitudinal and transverse directions.

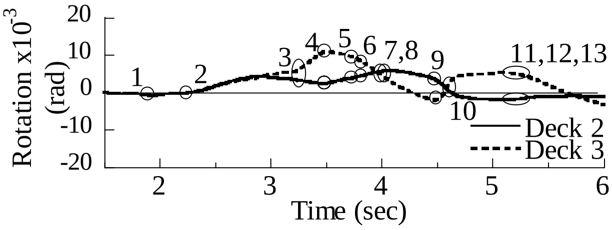
The NS and EW components of ground accelerations recorded at JR Takatori Station during the 1995 Kobe, Japan earthquake as shown in Figure 4 are imposed to the bridge in the longitudinal and transverse directions, respectively.

3. BRIDGE RESPONSE WITHOUT LOCK OF BEARINGS

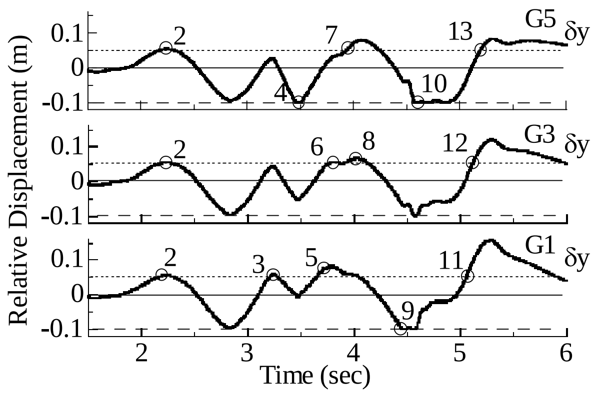
Figure 5 (a) shows the response displacement of Decks 2 and 3 as well as the response displacement of P2 in the longitudinal direction. Bearings which support Deck 3 on P2 progressively fail between 3.089 sec and 4.341 sec as shown in Figure 5 (b). G5 bearing fails first at 3.089 sec and subsequently G4, G3 G2 and G1 bearings fail at 3.113, 3.137, 3.163 and 4.341 sec, respectively. Because the restrainers resist excessive separation between the decks, the response displacements of the Decks 2 and 3 are virtually the same. However permanent residual displacements of 0.78 m and 0.75 m occur at the Decks 2 and 3 due to the failure of the bearings.

Figure 6 shows the responses of Decks 2 and 3, and Figure 7 schematically shows the decks movement during 1.875 sec and 5.243 sec. Times denoted as 1-13 in Figures 6 and 7 are the instances when the G1, G3 and G5 restrainers between Decks 2 and 3 yield and G1, G3 and G5 girders collide between Decks 2 and 3.

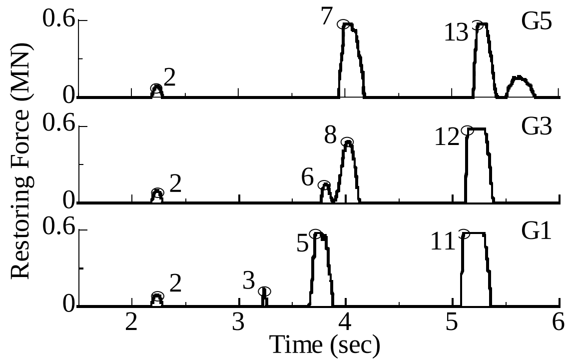
The relative displacement $\Delta u_{2,3}$ which is defined as the difference of response displacement at the end of Decks 2 and 3 on P2 ($\Delta u_{23} = u_3 - u_2$) reaches the restrainer gap of 50 mm at Time 2 as shown in Figure 6 (d). Consequently, PC cable restrainers start to resist further separation between Decks 2 and 3 resulting in tension force developed in the restrainers as shown in Figure 6 (c). At this instance, the tension forces developed in the G1, G3 and G5 restrainers are very similar because the relative rotations of both Decks 2 and 3 are very small as shown in Figure 6 (a). At Time 3, only G1 restrainer resists tension as shown in Figure 6 (c) because the clockwise rotation of Deck 3 is slightly larger than the rotation of Deck 2 (refer to Figure 6 (a)). However the peak tension force of G1 restrainer is only 0.09 MN which is 16 % the yield strength of the restrainer.



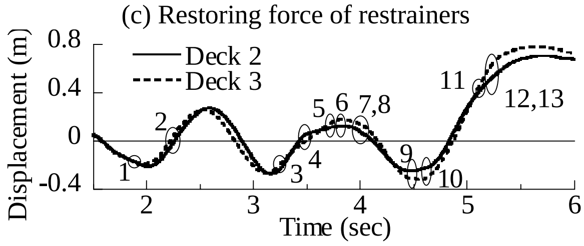
(a) Rotation of Decks 2 and 3 (θ_2 and θ_3)



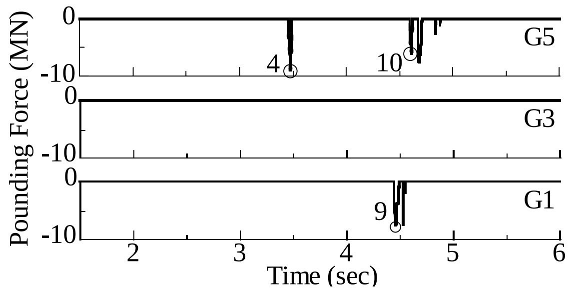
(b) Relative displacement between decks (Δu_{23})



(c) Restoring force of restrainers



(d) Response displacement of Decks 2 and 3
(u_2 and u_3)



(e) Pounding force between Decks 2 and 3

Figure 6 Rotation of the Decks, Restring Forces of Restrainers and Pounding Forces

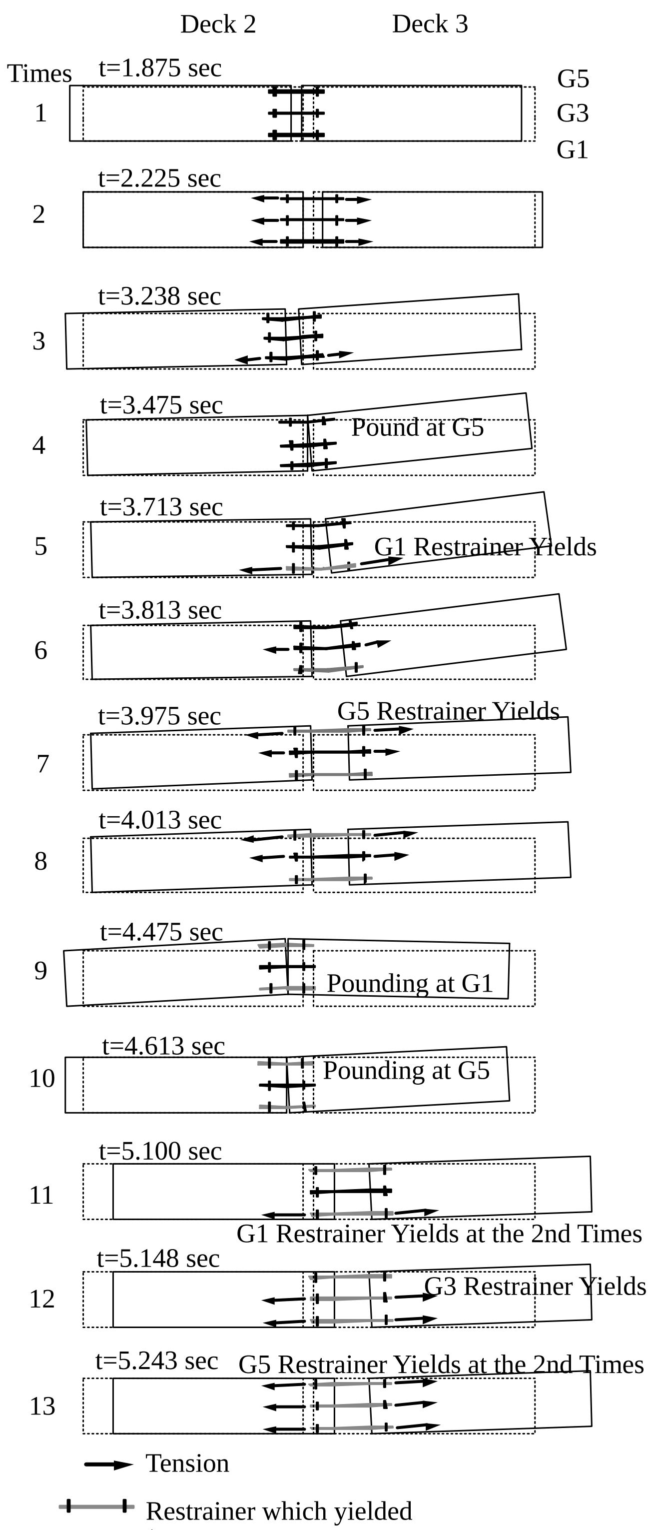


Figure 7 Deck Response with Poundings and Yielding of Restrainers

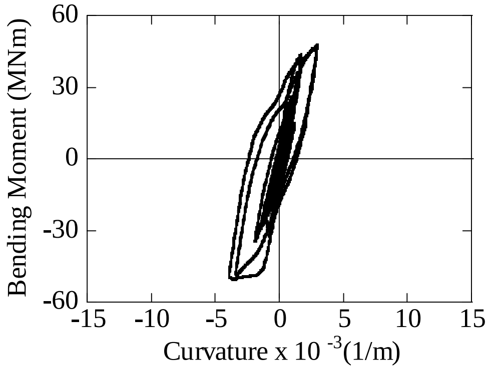


Figure 8 Moment vs. Curvature Hystereses of P2 at the Plastic Hinge in the Longitudinal Direction

Subsequently, Decks 2 and 3 collide at G5 at Time 4. The peak impact force is 9.0 MN which is equivalent to 1.38 times a deck weight. Because the collision occurred at G5, Decks 2 and 3 start to rotate in the anticlockwise and clockwise directions, respectively. Furthermore Deck 3 translates larger in the positive direction than Deck 2, and yielding of G1 restrainer occurs at Time 5 as shown in Figure 6 (c). It is noted that other restrainers have not resisted tension at Time 5. Then because Deck 3 rotates clockwise and Deck 2 rotates anticlockwise, G3 restrainer starts to resist tension at Time 6, however it is not yet yielded as shown in Figure 6 (c). Then G5 and G3 restrainers start to resist tension and yield at Time 7 and Time 8, respectively, as shown in Figure 6 (c).

Furthermore, large anticlockwise rotation of Deck 2 results in a strong collision of Decks 2 and 3 at G1 girder at Time 9 as shown in Figure 6 (d). The strong collision then changes the rotation of Deck 3 from clockwise to anticlockwise direction (refer to Figure 6 (a)), which subsequently results in a collision of Decks 2 and 3 at G5 girder at Time 10. Impact forces at Times 9 and 10 are 7.4 MN and 6.0 MN, respectively, which correspond to 1.13 and 0.92 times a deck weight. The two strong collisions result in separation of Decks 2 and 3, which result in second yielding of G1, first yielding of G3 restrainers at Times 11 and 12, respectively, followed by second yielding of G5 restrainer at Time 13.

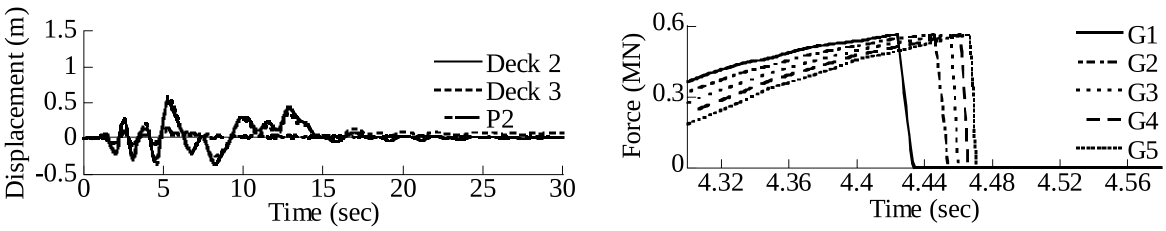
It is important to note that collisions of decks and resistance of restrainers for separation change the rotations and translations of the deck, which results in subsequent collisions between the decks and yield of the restrainers. Deck rotation develops collisions between decks and yielding of restrainers at the edge girders first followed by those at inner girders. This is a progressive failure mode of successive rupture of bearings and yield of cable restrainers. Therefore evaluation of the strength demand of restrainers by simply dividing the total seismic lateral force demand by number of the bearings and the restrainers underestimates the real strength demand of the bearings and the restrainers at the extreme edges.

Figure 8 shows the moment vs. curvature hysteresis of P2 at the plastic hinge. Because the curvature corresponding to yield 1.192×10^{-3} 1/m, P2 has already yielded.

4. EFFECT OF “LOCK” OF A BEARING AFTER FAILURE

The same bridge was analyzed assuming that G1 bearing which supports Deck 3 on P2 “locks” after failure, and that the lock limits the relative movement of the bearings from the failed position in both the longitudinal and transverse directions. Figure 9 (a) shows the response displacement of Decks 2 and 3 as well as the response displacement of P2 in the longitudinal direction. It is noted that the peak response displacements of Decks 2 and 3 are 0.53 m and 0.58 m, respectively. They are smaller than those of bridges without lock. Obviously the lock of G1 bearing limits the residual displacement of the Decks 2 and 3.

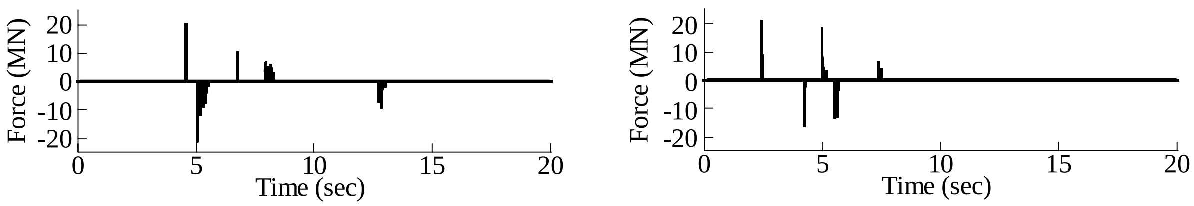
Among five bearings which support Deck 3 on P2, G1 bearing first fails at 4.424 sec, and subsequently G2, G3,



(a) Response displacement in the longitudinal direction (Decks 2, 3 and P2)

(b) Progressive failure of bearings which support Deck 3 on Pier 2

Figure 9 Response Displacement of Decks and Restoring Force of Bearings



(a) Longitudinal direction

(b) Transverse direction

Figure 10 Restoring Force of “Locked” G1 Bearing

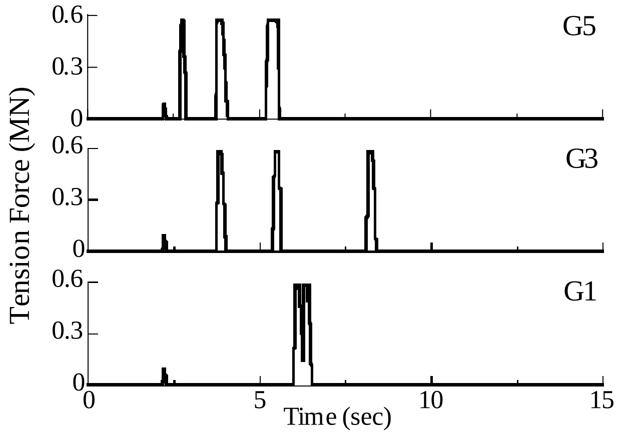


Figure 11 Restoring Force of Restrainers

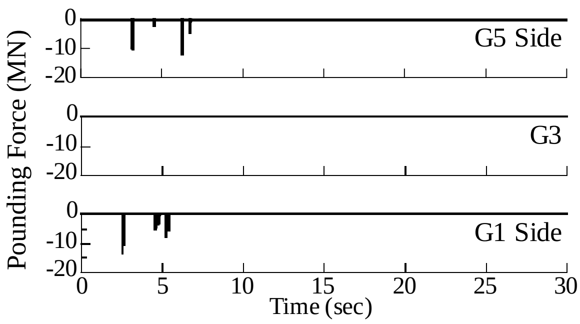
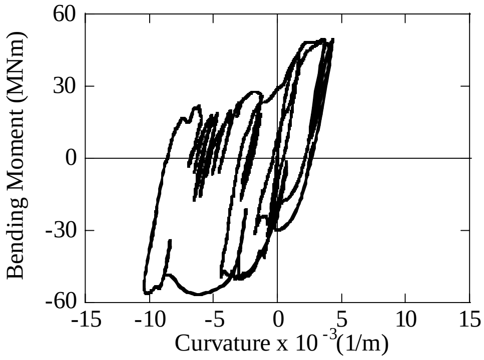


Figure 12 Impact Force between Decks 2 and 3

G4 and G5 bearings fail in this order at 4.446 sec, 4.455 sec, 4.461 sec and 4.467 sec, respectively. G1 bearing locks at 4.571 sec at the first time in the longitudinal direction, and G1 bearing subsequently locked 29 times, and G1 bearing locks first at 2.430 sec in the transverse direction and subsequently locked 19 times during the excitation. The locks result in transferring large lateral force from the decks to the piers. The peak forces generated by lock at G1 bearing are 21.1 MN at 5.070 sec and 20.8 MN at 2.436 sec in the longitudinal and transverse directions, respectively, as shown in Figure 10. They correspond to 3.20 times and 3.15 times a deck weight.

On the other hand, lock of G1 bearing results in more frequent yielding of cable restrainers as shown in Figure 11, compared to the response without considering the lock of a bearing (refer to Figure 6 (c)). Yielding of restrainers occurs first at G5 restrainer at 2.733 sec followed by the second yield at 2.788 sec. The lock of G1 bearing also results in more frequent pounding between Decks 2 and 3 as shown in Figure 12. The peak impact force at G1 girder reaches 13.5 MN, which is 179 % the peak impact force in the bridge without considering lock of G1 bearing.

Moment vs. curvature hystereses at the plastic hinge of P2 in the longitudinal direction is shown in Figure 13. Due to the large lateral force transferred by lock of G1 bearing, P2 exhibits significant hysteric behavior.



(b) Response with lock of bearing

Figure 13 Moment vs. Curvature Hystereses of P2 at the Plastic Hinge in the Longitudinal Direction

8. CONCLUSIONS

Effect of pounding between decks and progressive failure of bearings with/without lock was clarified for a 3-span bridge based on a nonlinear seismic response analysis. Based on the results presented herein, following conclusions may be deduced:

1. Relative opening and closure between two adjacent decks are larger at the extreme edges of decks resulted from combined rotation and translation of the decks. As a result, collisions between two adjacent decks first occur at the extreme edges of the decks and larger lateral seismic force applies to the bearings and restrainers at the extreme edges. Consequently, it is likely that failure of bearings and restrainers is initiated at the bearings and restrainers at an extreme edge, and propagates to the bearing and restrainers located at the center.

2. Evaluation of the strength of restrainers by simply dividing the total lateral force demand by number of bearings and restrainers underestimates the real strength demand of bearings and restrainers at the extreme edges. Enhancement of the strength demand of bearing and restrainers at the edges is required.

3. Restrainers are very important to control both the peak response and the residual displacement of decks in translation and rotation.

4. Lock of bearing which could occur due to rupture results in transfer of a large lateral force from a deck to the adjacent decks and piers. This can result in large plastic deformation in the piers. Because it is difficult to predict the locations where lock occurs, worst scenario has to be clarified based on the engineering experience and analysis.

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