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COMPARISON OF DYNAMIC RESPONSE OF REINFORCED CONCRETE BRIDGE PIERS USING SLOW AND REAL-TIME HYBRID SIMULATIONS

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Abstract

Hybrid simulation is an efficient testing method for investigating the seismic response of a structure. Unlike slow hybrid simulation, real-time hybrid simulation can effectively account for the rate-dependency of structures by imposing the target displacement on an experimental specimen in a real-time manner. In this paper, the loading rate effect of a reinforced concrete pier is experimentally investigated through the slow and real-time hybrid simulations. The concrete pier is used to support a two-span bridge. The nonlinear response of the bridge under earthquake loads is accurately accounted for by physically testing the concrete pier in a laboratory, while the superstructure of the bridge is analytically modeled. Prior to conducting hybrid simulations, cyclic load tests for the concrete pier are conducted with a predefined displacement history at different loading rates. Then, a series of slow and real-time hybrid simulations are conducted to investigate the loading rate effect on the seismic response of the concrete structure. It was found that the strength and the energy dissipation capacity of the concrete pier are increased with a high loading rate, where the global response of the bridge is also affected by the rate-dependency effect.

Keywords: rate-dependency; slow hybrid simulation; real-time hybrid simulation

1. Introduction

It is well known that concrete structures have a rate-dependent behavior due to the viscoelasticity of the bulk of the concrete and the rate process of the breakage of bonds in the fracture process zone [1]. A number of studies have been conducted to investigate the effect of rate-dependency of reinforced concrete structures on their dynamic response [2-4]. These studies are based on the comparison of an individual specimen subjected to predefined displacements with different loading or displacement rates (i.e., static and dynamic tests). The rate-dependency can cause the difference in the response of concrete structures, thereby the global response of a reinforced concrete structure can be also affected by the loading rate during the test. Therefore, it is important to include the rate-dependency effect during the test to understand better the critical dynamic response of concrete structures.

Conducting a shake table test would be a good method for such a study since the rate-dependency is automatically accounted for by having the shake table excited with the same acceleration time history as the earthquake ground motion. However, the cost for shake table test is expensive, especially when a large-scale structural system is used. Moreover, it is almost impossible to conduct a large-scale shake table test for structures such as long-span bridges and high-rise buildings due to the limited capacity of existing shake tables. Unlike the shake table test, hybrid simulation does not require a large amount of experimental cost since it only involves a physical specimen of our interest (i.e., the experimental substructure) to be tested in a laboratory, while the remaining structural components are analytically modeled (i.e., the analytical substructure). Therefore, a large-scale dynamic test can be performed in hybrid simulation with a much less amount of experimental cost than the shake table test.

Depending on the simulation speed, hybrid simulation is classified into two categories: slow hybrid simulation and real-time hybrid simulation (RTHS). In slow hybrid simulation, the displacement is slowly imposed on the experimental substructure over an extended time period, while being imposed in a real-time manner in a real-time hybrid simulation. The latter can consider the effects of rate-dependency of a structure. In this paper, the effect of rate-dependency on the dynamic response of a two-span bridge with a reinforced concrete pier in the middle is investigated by conducting slow and real-time hybrid simulations. The reinforced concrete pier in the middle is physically tested in a laboratory, while the remaining bridge structure is analytically modeled. By conducting a real-time hybrid simulation, the rate-dependency of the reinforced concrete pier is included in the simulation, and its effect on the global seismic response of the bridge can be investigated by comparing the results with those from the slow hybrid simulation.

2. Experimental test setup

Figure 1 shows a typical two-span bridge with pre-stressed concrete girders. A T-shape reinforced concrete pier is located in the middle of the bridge to support bridge decks and girders. In this bridge, non-linear deformations and structural damage would be predominantly concentrated at the bottom of the bridge pier under earthquake loads. Subsequently, other structural components including prestressed concrete girders and bridge decks would mostly remain linear elastic. Therefore, hybrid simulation using only the reinforced concrete pier can be an efficient testing method to effectively and reasonably investigate the seismic response of the bridge. The remaining structural components (bridge deck, girders, etc.) are analytically modeled, and the restoring force from the experimental substructure is fed into the equation of motion to obtain the structural response at the next time step by solving the equation of motion.

Figure 2(a) shows the experimental test setup for the reinforced concrete pier. For the simplicity of test setup, the pier cap beam was not manufactured. A horizontal dynamic actuator with a 100kN force capacity and 254mm stroke is connected to the pier at the top of the column. Considering the force capacity and the stroke limit of the actuator, a small-scale reinforced concrete pier was manufactured. The reinforced concrete pier has a square cross section with a size of 300mm by 300mm, as shown in Figure 2(b). The nominal height of the pier column is 1.7m and the effective height of the column (i.e., the distance from the base of the column to the centerline of the horizontal actuator) is 1.55m. The effective height of the column represents the distance from the base of the column to the hinge of the bridge shoe on the cap beam. With this test setup, there are eight tests conducted with eight RC pier specimens, as listed in Table 1.

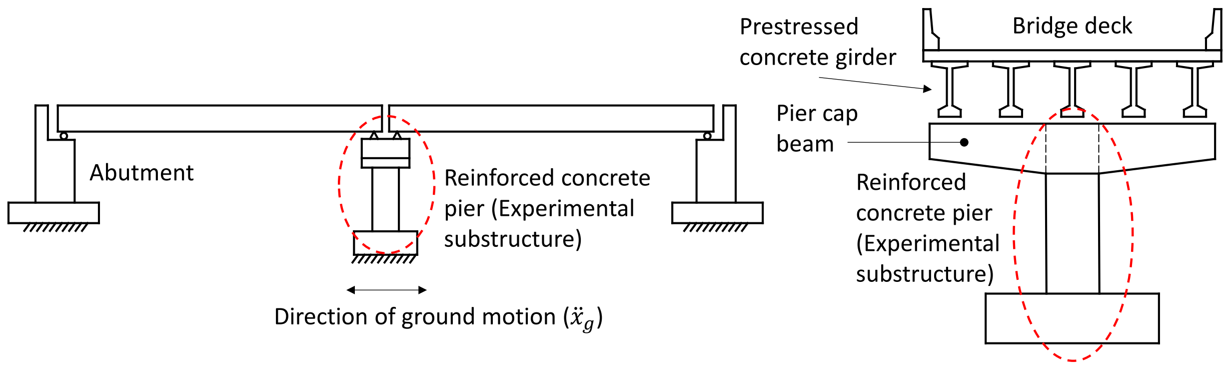
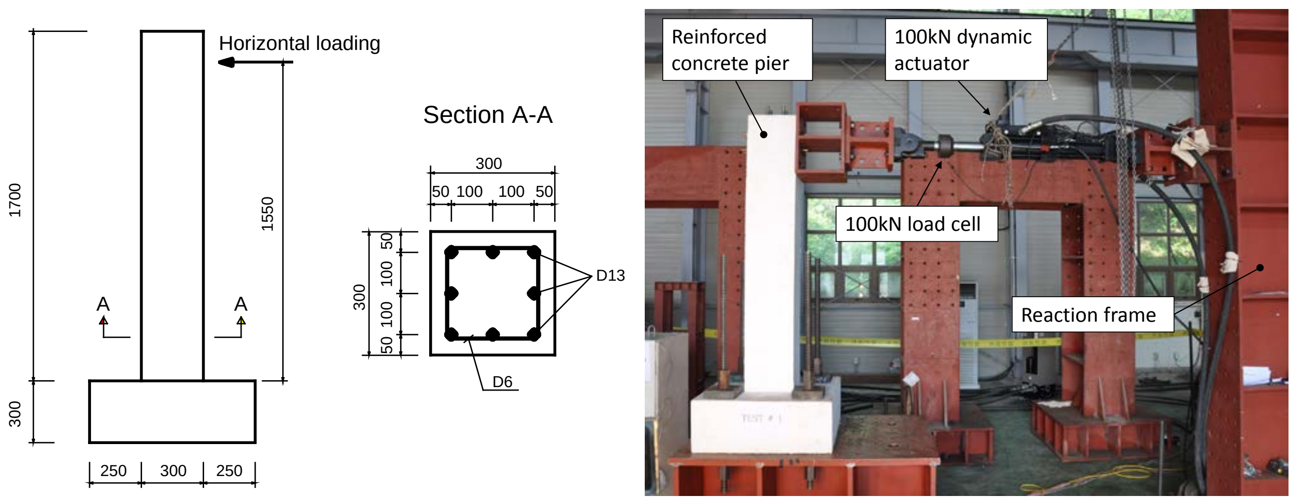


Fig. 1 A two-span prestressed concrete girder bridge



(a) (b)

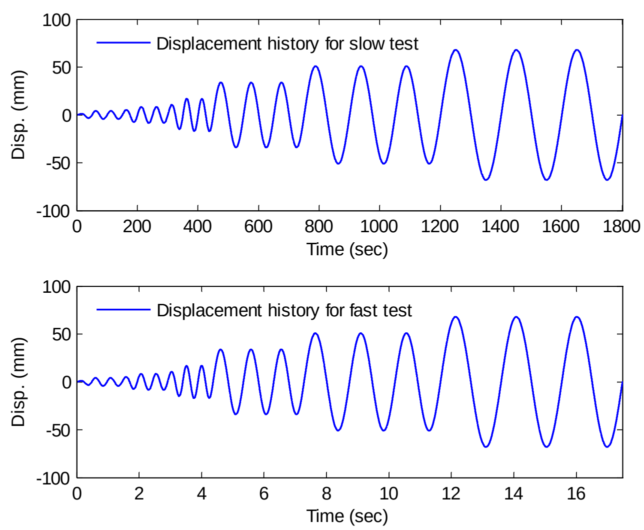
Figure 2. (a) Drawing for reinforcement bars (unit: mm); (b) Experimental test setup

Table 1. Test matrix

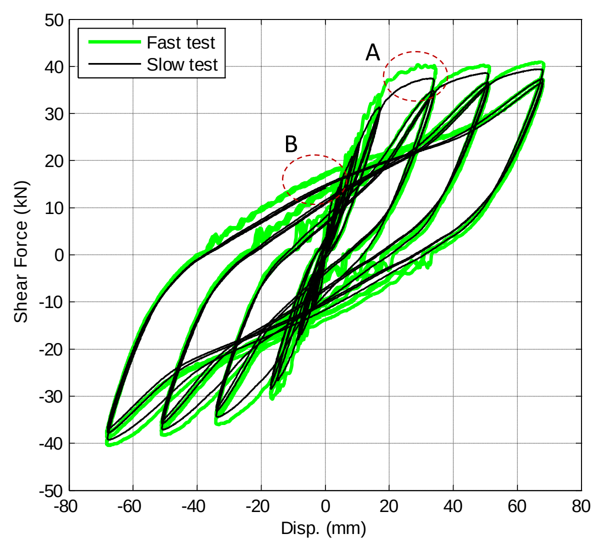
Test No.	Description
1	Predefined cyclic displacement test (slow)
2	Predefined cyclic displacement test (fast)
3	Slow hybrid simulation 1
4	Real-time hybrid simulation 1
5	Slow hybrid simulation 2
6	Real-time hybrid simulation 2
7	Slow hybrid simulation 3
8	Real-time hybrid simulation 3

3. Predefined cyclic displacement test

In order to compare the responses of the RC pier under different loading rates (i.e., different velocities), two different predefined cyclic displacement tests with the same displacement path, but with slow and fast rates each (hereafter, they are referred to as a slow test and a fast test, respectively), were conducted prior to conducting hybrid simulations. Figure 3(a) shows the displacement time histories for the slow and fast tests. In general, a displacement history with a saw-tooth type (i.e., a triangular shape) is used for a cyclic test of a concrete specimen. This type of displacement history can be smoothly implemented for a slow test. However, it is not appropriate for a fast test since there is a big velocity jump at the crest and trough of the saw-tooth wave, making it difficult to match the measured actuator displacement with the target displacement although a proper actuator control algorithm is used. Moreover, the velocity jump causes a large acceleration, subsequently producing a large inertial force of the RC pier. The effect of the inertial force needs to be minimized to better understand the rate-dependency effect of RC structures unless the accurate acceleration data for the entire RC specimen is given. In order to avoid the velocity jump, a series of sinusoidal waves with different amplitudes, as shown in Figure 3(a), is combined and used for the predefined cyclic displacement tests of this study. The displacement histories of both tests are exactly equal to each other, while the duration of each displacement history is different, i.e., 1,800 seconds and 17.48 seconds for the slow and fast tests, respectively. The maximum target velocities for the slow and fast tests are 2.1mm/sec and 220.0mm/sec, respectively. Having the same trace of displacement path for the slow and fast tests will lead to a better comparison and understanding of rate-dependency of an RC structure. During the fast test, the actuator was controlled by using the adaptive time series (ATS) compensation method [5] to match the measured displacement with the target displacement.



(a)



(b)

Figure 3. (a) Displacement time histories for slow and fast tests; (b) Force-displacement relationships of the RC bridge pier for slow and fast tests

Figure 3(b) compares the shear force vs displacement relationship of the reinforced concrete pier with different rates. As reported by many previous researchers, the yield strength of the reinforced concrete was increased when the displacement rate is fast (i.e., the fast test). The maximum lateral force resistances of the pier are about 40kN and 37kN for the fast and slow tests, respectively, during the sinusoidal cycle where the maximum displacement amplitude is 34mm (see ‘A’ in Figure 3(b)). This is equal to a strength increase of about 8%. The increase of the force capacity is also observed near zero displacement (see ‘B’ in Figure 3(b)). There is about a 3kN force difference between the fast and slow tests near zero displacement, where the velocity is maximum. Moreover, unlike the slow test, a high frequency fluctuation of force is observed during the fast test, which is attributed from the natural vibration of the pier due to dynamic loads during the test.

4. Hybrid simulations

For hybrid simulations of this study, the reinforced concrete pier is physically tested in the Hybrid Structural Testing Center (HYSTEC) at Myongji University, Korea. The remaining structural components of the bridge including the global damping of the system are analytically modeled. Assuming that only the longitudinal ground motion is applied and the axial deformations of the bridge decks and girders are negligibly small, the bridge can be simply modeled as a single-degree-of-freedom system of which equation of motion is given in Eq. (1).

$$m\ddot{u}(t) + c\dot{u}(t) + r(t) = -m\ddot{x}_g(t) \tag{1}$$

where, m is the mass of the bridge including decks and girders; c is the damping coefficient of the bridge; $u(t)$ is the horizontal displacement of the bridge decks/girders; $\ddot{x}_g(t)$ is the ground acceleration; and $r(t)$ is the experimental restoring force from the pier, which is obtained from the actuator load cell.

It is assumed that the natural period and damping ratio of the bridge are to be T=0.8 sec and ζ=5%, respectively. Based on the experimental initial stiffness obtained from the predefined displacement test, the analytical mass of the bridge is determined to be $m = k_{ini}(T\,/2\pi)^2$ ==64.85kN·sec2/m and the damping coefficient is $c = 2\zeta m(2\pi/T) =$ 50.93 kN·sec/m. The 1940 El Centro earthquake is used as an input ground motion for hybrid simulations, where the time history of the earthquake ground acceleration is shown in Figure 4. Due to the limitation of the velocity that can be achieved by the actuator, the input earthquake ground motion is scaled down with a factor of 0.7.

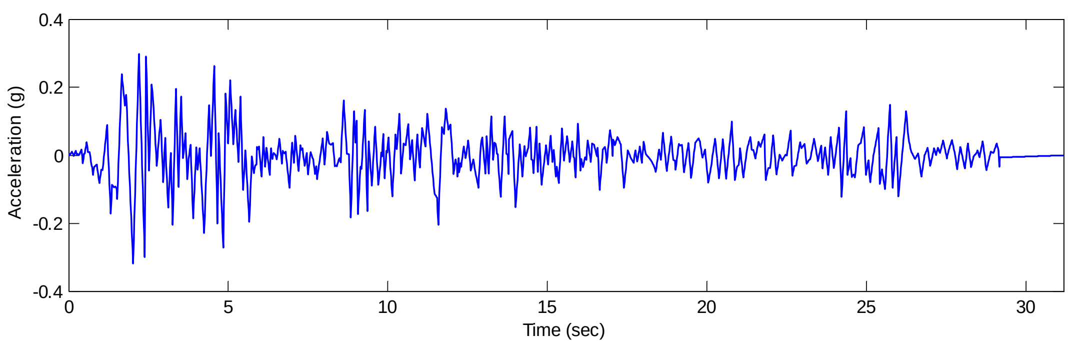


Figure 4. Ground acceleration of the 1940 El Centro earthquake (N-S component)

The hybrid simulations of this study are conducted by using the Matlab/Simulink tools and xPC by Speedgoat. Due to the limitation of using actuators, only a single actuator is used to impose the horizontal displacement. Satisfying the force boundary condition at the top of the pier is ignored in this study; this will exclude the axial load effect on the response of the pier from the hybrid simulations, including the axial load vs moment interaction and the P-Δ effect. The integration time step of each simulation is 1/1024sec (i.e., the sampling rate=1024Hz). The CR integration method [6] is used as a time integration algorithm to solve the equation of motion.

5. Slow hybrid simulation

The slow hybrid simulation is implemented by scaling the time axis of the original input ground motion, while preserving the value of ground acceleration to be the same as the original. The duration of the original El Centro earthquake is 31.18 seconds and this is expanded to be 1,995.5 seconds in the slow hybrid simulation, where the acceleration data is linearly interpolated into the newly scaled time data. This is a simulation with a 64 times slower rate than the real-time hybrid simulation. The effective force slowly changes during the simulation, making the dynamic effect negligibly small. Thus, the simulation becomes nearly static and the rate-dependency effect is minimal. Figure 5 shows the displacement of the bridge deck from the slow hybrid simulation (Test No. 5) under the 1940 El Centro earthquake.

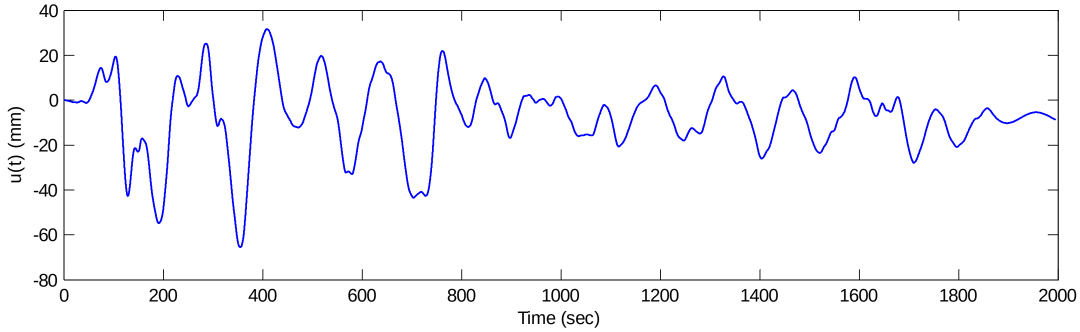


Figure 5. Displacement time history of bridge deck obtained from slow hybrid simulation (Test No.5)

5. Real-time hybrid simulation

In the real-time hybrid simulation, the original input ground motion is used without changing the time scale. Therefore, a displacement time history with real velocities would be imposed on the pier by the actuator, enabling the inclusion of the rate-dependency effect into the simulation. Since the real velocity is imposed on the specimen, an appropriate actuator control algorithm needs to be used to account for the delayed response of the actuator. In this study, the adaptive time series (ATS) compensator [5] is used for the real-time control of the actuator. The ATS compensator is designed for conducting a large-scale real-time hybrid simulation, and enables the actuator to match the target displacement well by adaptively adjusting its property to the response of the system, even the response is nonlinear.

6. Comparison of hybrid simulation results

Figure 6 compares the displacement response of the bridge from the two hybrid simulations under the 1940 El Centro earthquake. The time axis of the slow hybrid simulation is scaled down by a factor of 64 to match its time data with that of real-time hybrid simulation; thus, the displacement response from each simulation can be plotted together over the same time axis for a direct comparison. The maximum displacements of the bridge are obtained to be 65.5mm and 62.7mm for the slow and real-time hybrid simulations, respectively. The increased strength of the pier under fast rate resulted in a reduced response compared to the slow hybrid simulation. The increased yield strength of the pier can be observed in Figure 7(a) as well, where the force-displacement relationships are compared. Similar to the predefined displacement tests, the yield strength was increased by about 3kN and the force capacity near zero displacement (i.e., near maximum velocity) was also increased in the real-time hybrid simulation. These characteristics caused the increased capacity of energy dissipation, thereby, resulting in the reduced structural response. Figures 7(b) and (c) show the crack patterns of the pier. It is shown that similar flexural crack patterns were developed at the bottom of the pier in both hybrid simulations, but wider crack widths were predominantly observed in the real-time hybrid simulation.

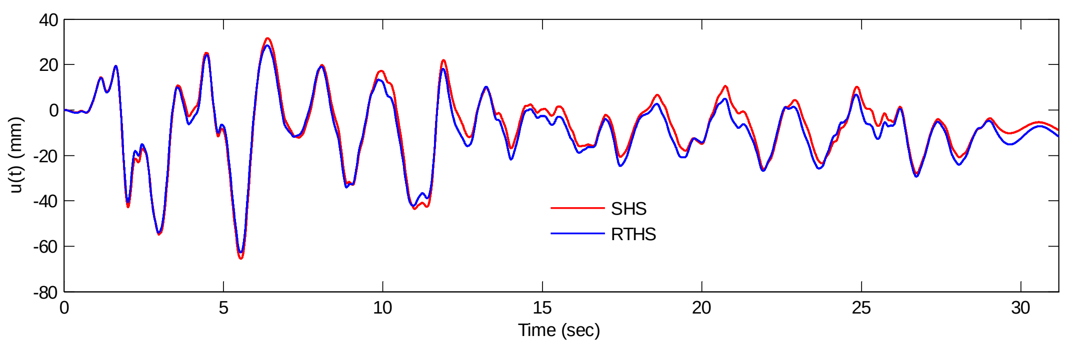


Figure 6. Comparison of displacement time history of bridge deck (SHS=slow hybrid simulation (Test No.5); RTHS=real-time hybrid simulation (Test No.4); time axis for SHS is scaled down by a factor of 64 to match the actual time scale of the input earthquake ground motion)

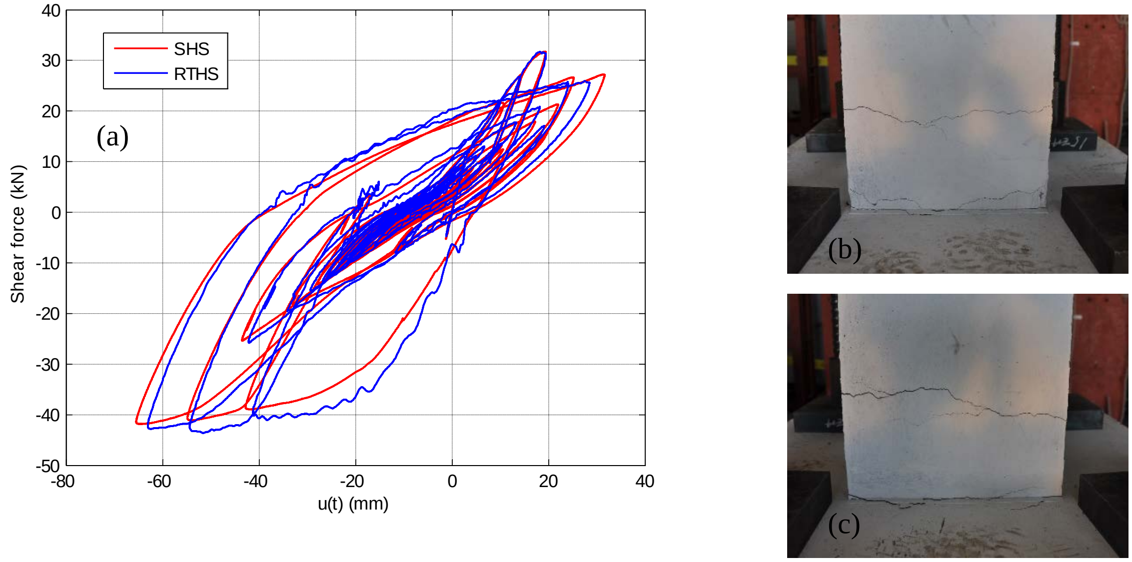


Figure 7. (a) Comparison of shear force vs displacement relationship of the pier (SHS=slow hybrid simulation (Test No. 5); RTHS=real-time hybrid simulation (Test No.4)); (b) Flexural cracks at the bottom of pier after SHS (Test No.5); (c) Flexural cracks at the bottom of pier after RTHS (Test No.4)

Table 1. Comparison of bridge global responses

	Slow hybrid simulation (SHS)				Real-time hybrid simulation (RTHS)			
	Test No.3	Test No.5	Test No.7	Average	Test No.4	Test No.6	Test No.8	Average
Max. displacement (mm)	66.1	65.5	63.6	**65.0**	62.7	62.6	60.0	**61.8**
Max. abs. velocity (mm/s)	319.0	317.4	317.0	**317.8**	316.5	314.6	313.4	**314.8**
Max. abs. acceleration (g)	0.126	0.125	0.125	**0.125**	0.126	0.125	0.125	**0.125**

Table 1 compares the global responses of the bridge between the slow and real-time hybrid simulations. Although there are some variations of test results among each test mainly due to the variation of concrete material properties, it is observed that the displacement response of the bridge is clearly reduced in the real-time hybrid simulation. As observed in the predefined displacement test, the increased strength and energy dissipation capacity at the fast rate result in the reduced displacement response during the real-time hybrid simulation. Unlike the displacement and velocity responses, no practical difference in the absolute acceleration is observed between the slow and real-time hybrid simulations. The increased strength generally increases the acceleration demand, while the increased damping ratio at the fast rate reduces the acceleration demand. As a result, this can lead to about the same acceleration responses between the two hybrid simulations.

7. Conclusions

In this paper, the dynamic response of a two-span bridge was compared through slow and real-time hybrid simulations. The bridge was modeled as a single-degree-of-freedom system, where the restoring force from the pier is experimentally obtained by using the servo-hydraulic actuator system. The inertial and damping forces of the system are analytically calculated and the response of the bridge is obtained by numerically solving the equation of motion. Prior to conducting a hybrid simulation, predefined displacement tests were conducted to investigate the initial stiffness and the rate-dependency effect of the pier. Then, a slow hybrid simulation and a real-time hybrid simulation were conducted to investigate the effect of the rate-dependency on the global response of the bridge under earthquake loads. The maximum structural response was reduced due to the increased capacity of yield strength and energy dissipation of the reinforced concrete pier at fast rates. However, it was observed that there is no significant difference in the acceleration response because the increased acceleration demand due to the increased strength is compromised by the increase energy dissipation capacity that can reduce the acceleration demand. Thus, conducting an experimental study that can include the rate-dependency effect would be more desirable to improve the accuracy of test results for investigating the dynamic response of reinforced concrete structures.

8. Acknowledgements

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