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REAL-TIME HYBRID TESTING OF SEISMIC PROTECTIVE SYSTEMS FOR BRIDGE STRUCTURES

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ABSTRACT

This paper presents a real time hybrid seismic test program that was carried out on bridge structures equipped with three different seismic protective devices: shock transmission units, viscous dampers and isolators with self-centering and friction energy dissipation capabilities. One of the structures studied also included bearing units with sliding interfaces providing additional energy dissipation capacity. In the hybrid tests, the seismic protective units were physically tested in the laboratory using high performance dynamic structural actuators imposing, in real time, the displacement time histories obtained from numerical simulations being run in parallel. The integration scheme used in the test program was the Rosenbrock-W variant and the integration was performed using the MathWorks's Simulink and XPC target computer environment. The numerical counterpart included the bridge piers and the additional energy dissipation properties. The nonlinear response of these components was accounted for in the numerical models. The tests were performed in the direction parallel to the length of the bridges and the deck was assumed as infinitely stiff. The tests were run under various ground motions and the influence of modeling assumptions such as damping and initial stiffness was investigated. Finally, the test results were compared to the predictions from dynamic time history analyses performed using commercially available computer programs. The results indicate that simple numerical modeling techniques can lead to accurate prediction of the displacement response of the bridge seismic protective systems studied.

Introduction

Bridges are critical structures that must be designed to withstand natural hazards such as earthquakes. In Canada, seismic activity in highly populated areas exists along the Pacific west coast in western Canada and along the St-Lawrence and Ottawa River valleys in eastern Canada. Seismic design provisions have been progressively implemented in CSA-S6 Canadian Highway Bridge Design Code starting in 1966 (CSA 1966) but only minimum earthquake horizontal

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design loads were prescribed until 1988 (Bruneau et al. 1996). Additional seismic load requirements for bearings and qualitative ductile detailing provisions for reinforced concrete columns were introduced in 1988, but it is only in 2000 that explicit seismic detailing requirements and capacity design principles were introduced in CSA-S6. Between the 1966 and the latest editions of CSA-S6 (CSA 2006), the prescribed seismic design forces have also steadily increased. A recent study revealed that the average age of bridges and overpasses in Canada had exceeded 57% of their service life of 43.3 years in 2007 (Gagnon et al. 2008). That number increases to 72% in the Province of Quebec, the highest in the nation, indicating that the vast majority of the existing bridges in the eastern Canada seismic active region may be at risk and require seismic retrofit. Seismic hazard also significantly impact the construction of new bridge structures as a result of the increasing severity and complexity in seismic detailing and the higher seismic design loads prescribed in recent code editions. In this context, there is an increased need for innovative techniques to achieve time- and cost-effective seismic retrofit and construction of bridge structures. Although seismic base isolation has been known since the beginning of the 20^{th} century, it was introduced in North America only in the 1980's (Guizani 2003). In Canada, seismic isolation for bridge retrofit has been applied in British Colombia since the early 1990's (EERC Protective Systems 2009). In Québec, the first seismically isolated bridge structure was built in Alma in 2002 (Guizani 2003). The same year, seismic dampers and shock transmission units (or lock-up devices) were implemented for the first time in a bridge retrofit project in Quebec City (Loulou et al. 2003). This paper reports on a study of the dynamic response of bridge structures equipped with friction isolators, viscous dampers and shock transmitting systems when subjected to seismic demand from earthquakes expected in eastern North America. An extensive experimental program consisting of Real-Time Dynamic Substructuring (RTDS) of the seismically isolated bridges was conducted. RTDS testing is based on a sub-structuring technique where the investigated system is split into: (i) a physical sub-structure consisting of a critical part or component tested experimentally under dynamic forcing, and (ii) a numerical sub-structure modeling the reaction of the remaining part of the system. To realistically emulate the behavior of the whole system during dynamic excitation, the control strategy and numerical algorithms are conceived so that the physical and numerical substructures interact in real time. A significant advantage of RTDS testing is that the physical sub-structure can be tested at full scale while including dynamic and hysteretic effects through real time interaction between the physical and numerical substructures. This hybrid technique was first proposed by Nakashima and Takaoka (1992) as an important improvement of the pseudo-dynamic testing method introduced by (Takanashi et al. (1975). Real-time hybrid simulation has been successfully applied recently to assess the dynamic response of structures equipped with seismic protective devices (Christenson et al. 2008; Fujitani et al. 2008). In this work, special attention is devoted to investigating the effects of high frequency content ground motions typical of Eastern North America. Nonlinear time-history analyses of the seismically-protected bridges are also carried-out and the numerical predictions are validated against RTDS testing results.

Seismic protective devices studied

Friction device

The innovative Friction-based Seismic Protective System (FSPS) tested in this work is manufactured by Goodco Z-Tech (Goodco-Z-Tech 2009). It consists of: (i) a stainlesssteel/PTFE friction interface which provides isolation and energy dissipation, and (ii) linear elastic metallic coil springs which provide stiffness and self centering capacity. In 2002, a similar device was installed on the first base-isolated bridge in Quebec, located in Alma on highway 169 (Guizani 2003), and more recently on a bridge on highway 20 over the Nicolet River (Guizani 2007). An elevation view of a typical FSPS is illustrated in Figure 1 (f). The FSPS investigated in this work has a bilinear hysteretic behaviour characterized by: (i) an initial stiffness, nearly infinite, corresponding to gaps or minor deformations in the isolator, and (ii) an elastic limit F_y given by the force developed at the friction interface, which can be evaluated as:

$$F_y = \mu W \tag{1}$$

where μ denotes the friction coefficient at the interface, and W the vertical load on the bearing. The coil springs of the friction device define the post-elastic stiffness of the bilinear system.

Viscous devices

Two other innovative seismic protective systems were also investigated in this project: (i) a Seismic Damping Unit (SDU), (ii) and a Shock Transmission Unit (STU). Both devices are manufactured by LCL-Bridge Products Technology (LCL-Bridge Products Technology 2009). They are made of a double-acting piston driving a fluid through a parallel set of tubular orifices, thus producing fluid shear to resist dynamic movement (Calvi et al. 2007). The SDU offers little to no resistance to slow movement, such as thermal expansion, creep and shrinkage, while it reduces dynamic movements due to braking or seismic loads through energy dissipation. The STU also allows slow movement, while offering an increasingly higher resistance to faster movement due to braking or seismic loads. Contrary to most lock-up systems, the STU tested in this work is designed so that the reacting force does not exceed an upper limit and, thereby, control the force demand imposed to the columns or abutments. Both types of devices were used recently to retrofit a bridge over Highway 440 in Quebec (Loulou et al. 2003). The reacting force F of a viscous damper can be expressed as:

$$F = C_p V^{\alpha} \tag{2}$$

where C_p denotes the damping coefficient, V the velocity of the piston and α a characteristic parameter. Typically, the parameter α varies between 0.1 and 2.0, with $\alpha > 1.0$ for a shock transmission device and $\alpha \leq 1.0$ for a viscous damper. In the latter case, the damper is linear when $\alpha = 1.0$, and nonlinear otherwise. For the STU device investigated in this work, a parameter $\alpha < 1.0$ was used in view of its force limiting capabilities. The two devices have the same exterior appearance and only differ by the design of the internal fluid flow system design. Figure 2 (c) shows an elevation view of SDU or STU.

Bridges studied

Bridge with friction device

The seismic response of an actual bridge equipped with the FSPS was investigated. The bridge overpasses the Nicolet River in Quebec and four spans of 27.761 m, 36.627 m, 36.599 m, and 27.815 m as shown in Figure 1 (b). The bridge deck has a total mass of 1580 t and is made of a concrete slab supported by four steel girders. The bridge columns are of reinforced concrete hammerhead wall type as depicted in Figure 1 (e). The bridge longitudinal response was examined in this study. The bridge deck is seated on three sets of four sliding bearings mounted on the western abutment A1 and piers P2 and P3, respectively, a set of four friction-based energy dissipation devices mounted on pier P4, and a set of four FSPS mounted on eastern abutment A5. The values of the coefficients of friction μ of the numerically modelled bearings were varied in order to conduct a parametric study on the influence of this modelling assumption. For the sliding bearings of supports A1, P2 and P3, μ was taken as 0.5 %, 1% or 3%. The value of 3% was chosen to consider an aged condition for the friction interface. For the friction energy dissipation devices of support P4, μ was taken as 8% or 11%. The flexural stiffness of the bridge columns is determined taking into account their geometrical configuration and the skew angle of the bridge. An effective cracked column moment of inertia of 70% of the gross moment of inertia is assumed, resulting in column lateral stiffnesses along the longitudinal axis of 50.8 MN/m at P2, 74.5 MN/m at P3 and 52.5 MN/m at P4.

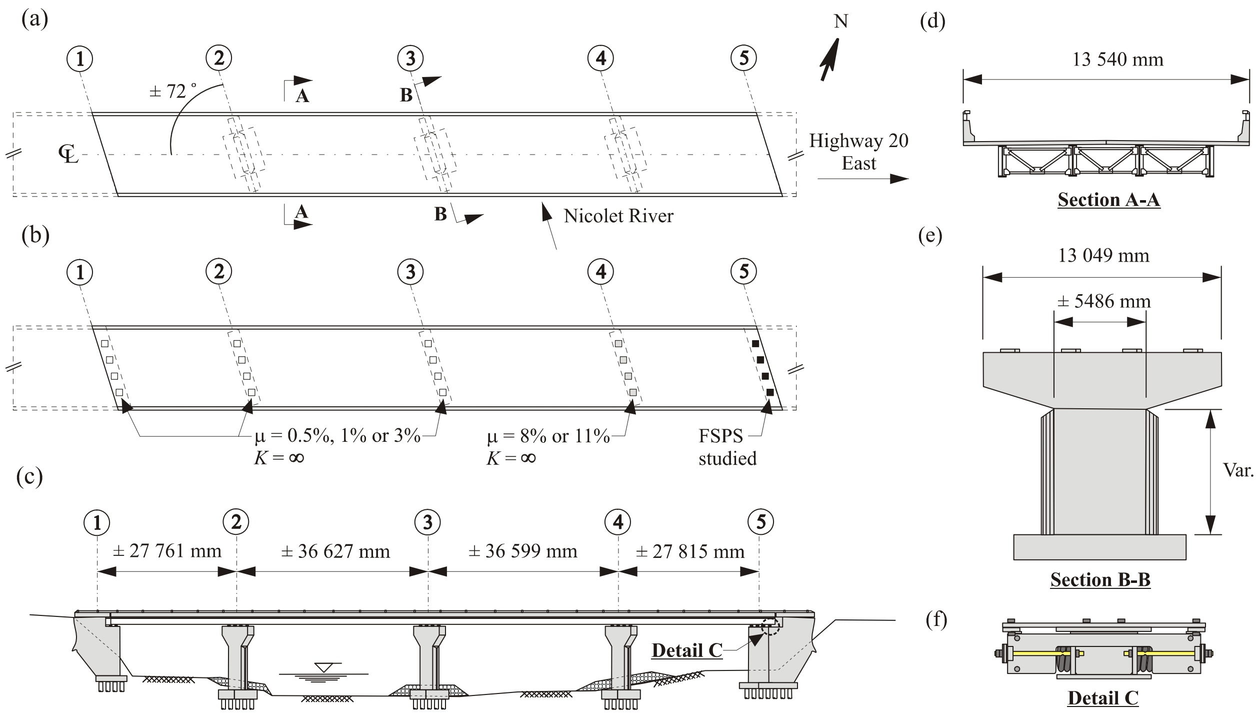

Figure 1. Bridge with FSPSs: (a) Plan view; (b) Bearing properties; (c) Elevation; (d) Deck; (e) Pier; (f) FSPS.

Bridge with viscous devices

A fictitious bridge structure assumed to be located in Montreal, QC is considered to investigate the seismic performance of bridges equipped with viscous seismic protective devices. The bridge selected is straight and has two spans of 36.7 m each as illustrated in Figure 2 (a). The bridge deck consists of four T-shaped reinforced concrete beams and has a total mass of

2560 t. The bridge deck is supported at mid-span by two reinforced concrete hammerhead wall columns placed side by side as illustrated in Figure 2 (b). The bridge longitudinal response was examined in this study. Along this direction, the bridge deck is fixed to the columns and free to translate at the two abutments. The abutments are assumed infinitely stiff and two seismic protective devices are introduced between the deck and one of the abutments. An effective moment of inertia of 42% (for the SDU equipped bridge) and of 36 % (for the STU equipped bridge) of the gross moment of inertia of the columns was considered, to account for concrete cracking, resulting in a column lateral stiffness along the longitudinal axis of 60.9 and 43.5 kN/mm, respectively. The assumed columns' longitudinal yield strength is 3200 kN for the SDU equipped bridge and 500 kN pour the STU equipped bridge.

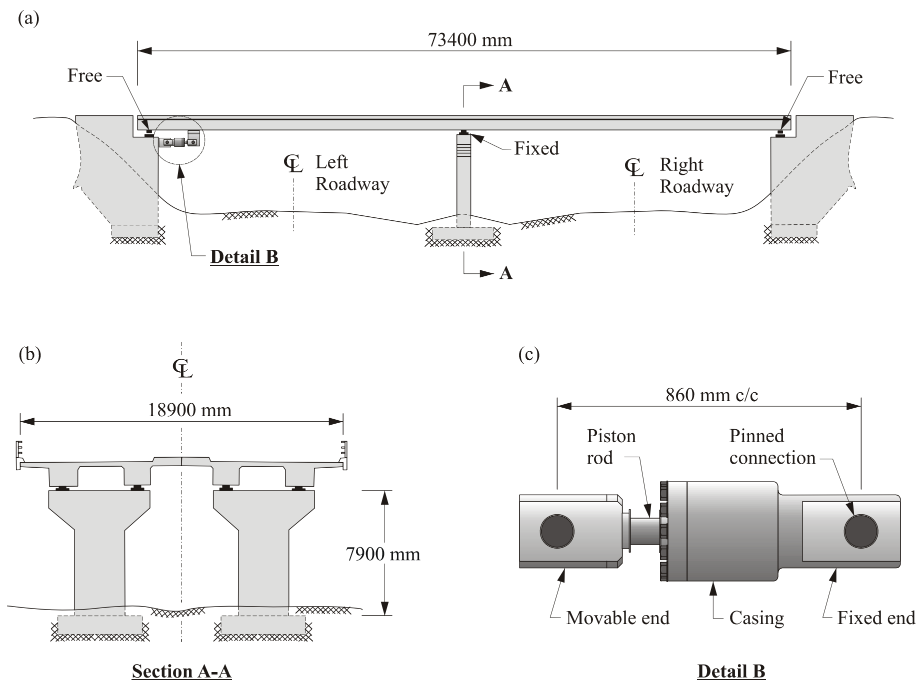

Figure 2. Bridge with viscous devices: (a) Elevation; (b) Column and deck; (c) SDU or STU.

RTDS testing program

Test setup and protocol

The displacement command was imposed to the tested devices using high performance dynamic actuators. The test setup used to conduct the RTDS simulation on the SDU/STU equipped bridges is illustrated in Figure 3. In the setup for the FSPS equipped bridge, static hydraulic actuators were used to impose the vertical force corresponding to the deck weight supported by one isolator device. The testing protocol consisted of dynamic cyclic tests to characterize the devices and of RTDS simulations on the seismically protected bridges subjected to earthquake loads. The STU equipped bridge was also subjected to vehicle braking forces during the RTDS test program. For the cyclic tests, harmonic sinusoidal and triangular displacement histories with varying amplitudes and frequencies were imposed. For RTDS testing, twelve synthetic high frequency content seismic ground motions typical of eastern North

America were used. The records correspond to M_w 6.0 or M_w 7.0 events at site-to-source distances (R) that dominate the seismic hazard for site class C in Montreal, Quebec, for a probability of exceedance of 2% in 50 years (Tremblay and Atkinson 2001). The accelerograms were scaled to the 2% in 50 years uniform hazard spectra at the site and were applied along the longitudinal direction of the bridge.

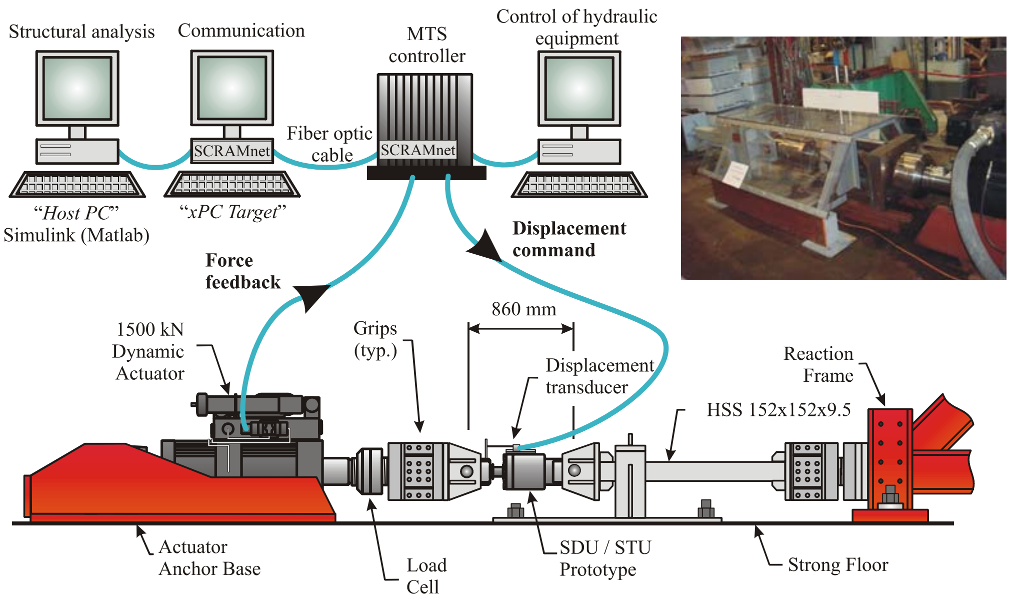

Figure 3.Test setup for the viscous devices.

RTDS control method

In a RTDS simulation, the physical and numerical substructures interact in real time to simulate the global response of the bridge structure. This RTDS simulation is conducted using a control system consisting of a simulation PC and a control PC, as illustrated in Figure 3. The simulation PC uses an integration scheme implemented in Simulink (Simulink® 2007) to solve the equations of motion for the target displacement imposed to the physical substructure at each time step of 1/1024 second. The target displacement is communicated to the target PC which, in turn, communicates it to the MTS servo-controller through a SCRAMNet fiber optic local area and shared memory network capable of transferring information at a high frequency rate. The control PC, which communicates in parallel with the servo-controller, is needed to control the hydraulic equipment. The control system uses a variant to the Rosenbrock-W time integration scheme developed by Lamarche et al. (2009).

Numerical models

The deck of the bridge is assumed infinitely stiff axially and the bridges can then be represented by the Single Degree of Freedom (SDOF) systems shown in Figure 4 (a). In the RTDS tests, the numerical substructures consist of the bridge columns and the mass of the deck, M, and, in the case of the FSPS equipped bridge, the friction bearings. The stiffness of the columns varies assuming a bilinear hysteresis rule. Mass proportional Rayleigh damping equal to

5% of critical damping was assumed to take into account energy dissipation in the bridge. This is represented by the damping parameter C_n of the numerical substructure:

$$C_n = 2\xi\sqrt{K\,M} \tag{3}$$

where the viscous damping factor $\xi = 0.05$. In the case of the SDU/STU equipped bridge, the physical substructure comprises two viscous devices, and in the case of the FSPS equipped bridge, it comprises four friction devices. As illustrated in Figure 3, only one device was physically tested in the laboratory and the force feedback from the actuator load cell was multiplied by the appropriate factor (2 or 4) in the model. For the purely numerical analyses performed in SAP2000 and in ADINA (ADINA 2008), the software's predefined elements were used to model the seismically protected bridges, such as plastic elements defined by bilinear hysteresis rules to model the piers and the friction devices, and viscous damper elements programmed with a reacting force defined by Eq. 2.

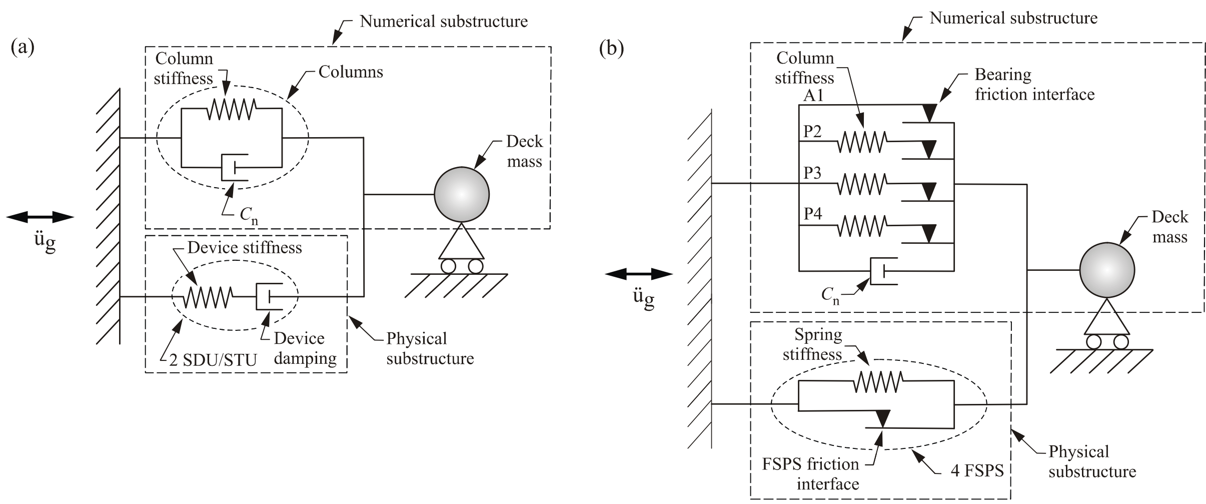

Figure 4. Numerical models for bridges equipped with (a) FSPSs and (b) viscous devices.

Results

Specimen characterization

Examples of force-displacement hysteretic curves obtained for a single device submitted to cyclic tests performed at varying frequencies are illustrated in Figure 5. The specimen mechanical properties were obtained from these cyclic tests series, i.e. coefficient of friction μ and coil spring stiffness K for the FSPS and viscous damping properties C_p and α for the SDU and STU.

RTDS testing and numerical model validation

A parametric study on the influence of certain modeling assumptions such as damping and column stiffness was conducted through RTDS simulations of the protected bridges subjected to the synthetic accelerograms described previously. Figure 6 illustrates examples of the dynamic responses of the bridges from RTDS tests compared to purely numerical simulations. In the SAP2000 model, the specimen parameters are those obtained from the specimen characterization tests and excellent match is generally observed between the two simulations. Similar agreement was obtained under the other ground motions. This shows that it is possible to predict the longitudinal displacement demand on bridge structures equipped with the three studied devices using a simple SDOF numerical model and a commercially available computer program.

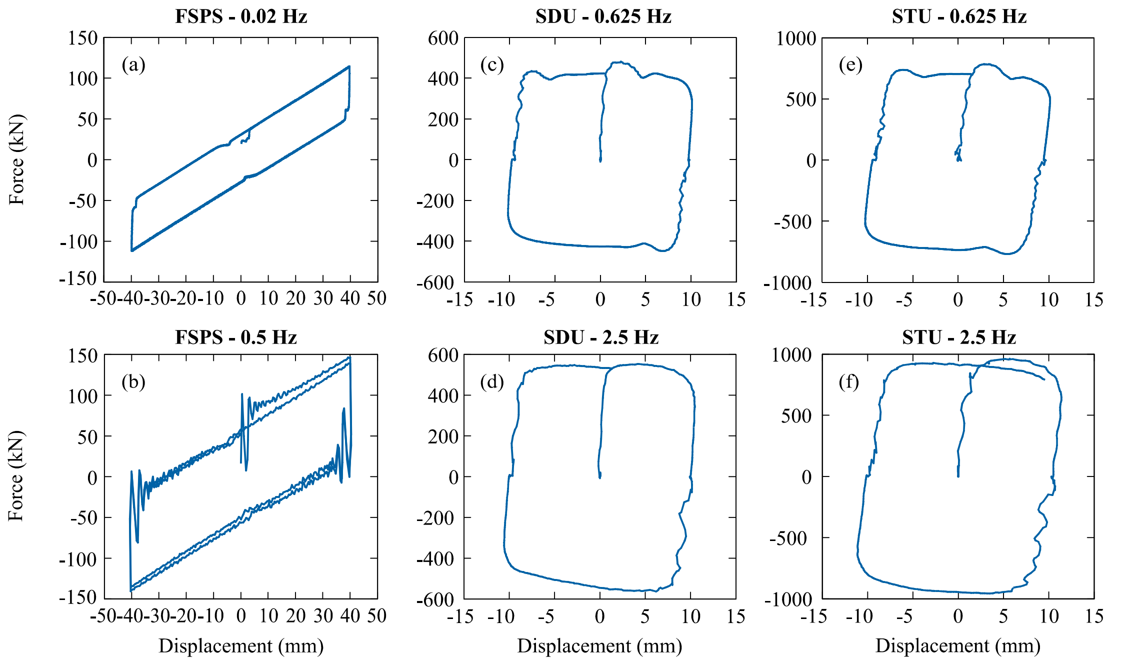

Figure 5. Specimen force-displacement relationship from triangular (a, b) or sinusoidal (c, d, e, f) signals from cyclic tests.

Conclusions

In this work, an RTDS simulation program was successfully performed to assess the dynamic performance of bridge structures equipped with three types of seismic protective devices: friction seismic protective systems (FSPS), seismic damping units (SDU) and shock transmission units (STU). The response of the bridge structures was studied along its longitudinal direction and the structures were subjected to strong ground motions rich in high frequencies that are expected to occur in Eastern North America. Purely numerical simulations were run in parallel with the tests in SAP2000 for comparison purposes. RTDS tests were used to investigate the effects of different modeling assumptions and validate the numerical predictions of the nonlinear time-history response of seismically protected bridges. Prior to RTDS testing, the devices were characterized through cyclic dynamic testing. The obtained mechanical properties were included in the numerical substructure used for the RTDS tests as well as into the finite element models of the seismically protected bridges. The study also showed that the longitudinal displacement response of FSPS/SDU/STU-equipped bridge structures can be numerically reproduced with simple SDOF models including elements currently available in commercially available computer programs such as the SAP2000 program, provided that the properties are well known.

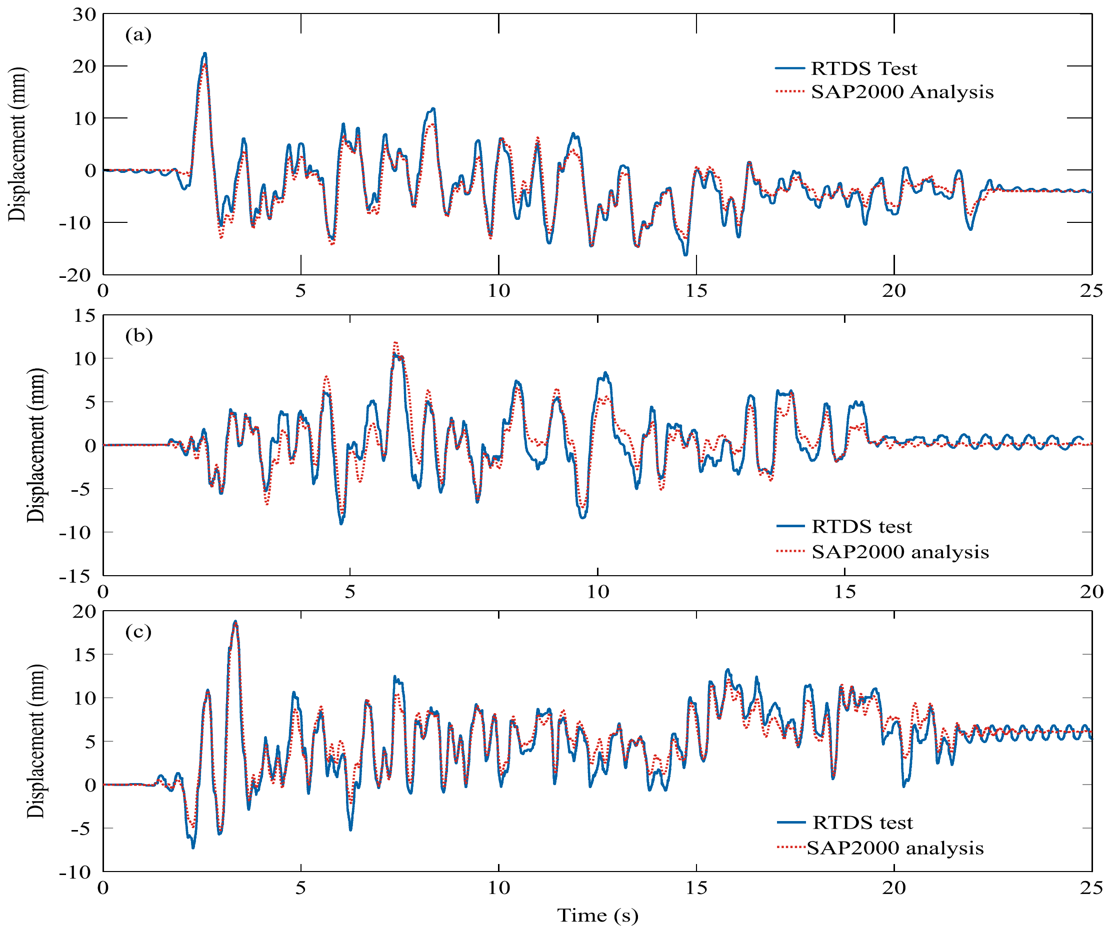

Figure 6. Displacement time-histories obtained from RTDS tests and SAP2000 numerical analysis for (a) FSPS under earthquake M_w 7.0 at R=70 km, (b) SDU under earthquake M_w 7.0 at R=30 km and (c) STU under earthquake M_w 7.0 at R=100 km.

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