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Virtual Laboratory for Studying Seismic Response of Base Isolated Bridges*

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Seismic isolation and energy dissipation are used for improving the dynamic response of bridges. However, no general concept for selecting the most appropriate devices for each structure is available, therefore understanding the dynamic processes is important for the selection and design of proper energy dissipation system to improve bridges' dynamic behavior. This study is focused on an active training method for studying the behavior of bridges with base isolation systems under earthquakes. The proposed method includes creating and testing of bridges' numerical models in the classroom, and further results' analysis by the students, aimed at drawing practical conclusions under the teacher's supervision. To implement the method in the learning process, a Bridge Dynamics Laboratory was created in the Simulink environment. Original libraries of bridge's structural elements, anti-seismic devices and seismic loads were developed. Modeling bridges using these libraries is a simple procedure, being easily incorporated in the learning process during class teaching. Simulink allows the development of bridge models that visually reflect the real physical processes, involving the bridge structure, and provides the possibility of quick and convenient modification of any parameter characterizing the model. The learning process includes the representation and measurement of structural behavioral parameters, and their dependence on types and technical characteristics of the applied seismic protection system. Dynamic processes are studied based on modern standards. Time-history analysis is used to simulate the investigated bridge behavior under a selected earthquake. Implementation of the proposed method in the classroom teaching process of an undergraduate course is presented and explained.

Keywords: virtual laboratory; base isolation; bridges; seismic response; engineering education; Simulink

1. Introduction

Studying methods and devices for improving structural response to earthquakes, wind, man-made and other dynamic loadings is a very important stage in undergraduate civil engineering education. In the last three decades, base isolation and passive energy dissipation have undergone great developments, and have been extensively applied in existing and new conventional bridges as well as in modern suspended and cable-stayed ones [1]. As each structure has individual dynamic parameters, it is difficult to develop general seismic protection concepts [2], therefore each structure should be designed for appropriate loads to select the most suitable protection system for each specific project.

An in-depth understanding of structural dynamic behavior is very important for the proper selection of the seismic protection system that should be applied in order to improve the response of bridges to earthquakes. Visual representation of changes in bridge dynamic parameters over time for different types of seismic protection systems enables easy understanding of complicated dynamic processes and allows undergraduates to gain the theoretical knowledge.

A known and often used method to visualize dynamic processes is to test physical models of structures in the laboratory [3, 4]. Implementation of this method is, however, limited by the substantial costs, which increase as more parameters are measured and observed. As bridges represent very heavy and long systems, it is difficult to obtain reliable results by physical testing using shake tables. Additionally, a bridge is usually a multi-support system. Therefore physical modeling in the laboratory, considering different excitations under various bridge supports, may require using several vibrating tables, which is complicated within the frame of a laboratory designed for educational purposes.

A "virtualized laboratory" was introduced at the University of California for earthquake engineering education to capture and disseminate the results of shake table experiments [5]. It was reported that virtualized experiments can provide students with a new mechanism to observe, explore, analyze, and conceptualize complex physical experiments in digital form. These experiments can be studied at any time, and at any place equipped with a commodity computer, or within a new generation of emerging information technology classrooms.

Another Java-powered virtual laboratory (VL) was developed at University of Illinois for undergraduate and graduates to carry out online interactive structural dynamics experiments [6]. A multistory one-bay shear framed building was employed as a test bed, and the responses of the

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structure were obtained through linear/nonlinear dynamic analysis in order to gain a fundamental understanding of these topics by conducting online numerical experiments using these interactive VLs. It was reported that these online VLs provide an alternative way for students and practitioners to develop their knowledge of earthquake engineering. The VLs provide users with wide flexibility to configure system parameters, conduct analysis, and view results.

MATLAB is the software that is often chosen for teaching engineering students because of its ubiquitous use in engineering studies and practice. It is widely available to students on school networks and through inexpensive educational versions, making MATLAB a great tool for teaching scientific computation [7]. Practicing programming throughout the undergraduate program allows students to acquire proficiency in a methodology of solving a wide variety of engineering problems that cannot be solved by manual calculation [8].

A MATLAB-based educational software was developed at Aristotle University, Thessaloniki, to acquaint students and young engineers with the fundamental concepts of structural dynamics and, in particular, soil–structure interaction problems [9]. The software was also used for demonstrating the strategy required to develop realistic earthquake engineering-oriented MATLAB applications. It was suggested that the particular educational framework is a promising application of information technologies in developing courses for teaching, evaluating, examining, and supporting students solely using the proposed software.

Since the existing programs of structural nonlinear time-history seismic analysis are limited in their visualization and exploration potential, simulations of a nonlinear seismic response of multistory one-span shear building models based on MATLAB's Simulink were developed [10]. It was shown that simulations of structural nonlinear seismic responses using Simulink are feasible and reliable. The advantages of using Simulink simulations for these purposes include visual simple establishment of the model and the possibility to present complicated dynamic analysis by the simplest simulation means. It was also concluded that the development of the model has high succession and a powerful further development function. As the realization of structural elastic–plastic dynamic analysis using Simulink is completely executive and predominant, the advantages of structural nonlinear analysis and structural vibration control can become an attractive research prospect.

The present study deals with an alternative method for modeling structural dynamic behavior, aimed to create and test virtual models in the classroom, analyze the results, and draw practical conclusions under the instructor's supervision. Following this method, laboratory class work progresses through a predefined sequence of actions including scheme assemblage, connection of measurement devices and results analysis. The proposed modeling method uses Simulink capabilities. It is based on structural models created by students using blocks of structural elements, anti-seismic devices, and seismic loads, available from the libraries that had been originally developed by the authors.

This method allows students to create complex structural models independently, quickly and conveniently, and to apply a system for measuring and visualizing the results for each problem investigated. This method facilitates an in-depth understanding of structural dynamics, including complicated dynamic processes such as energy dissipation, seismic isolation, interaction between a bridge and protection system, etc.

In the frame of the laboratory students create investigated structural models, visualize various dynamic processes by representing and measuring structural dynamic parameters and dependencies of these parameters on the type and parameters of seismic protection systems (supplemental dampers, base isolation systems, active control devices, etc.) and their combinations.

Simulink visualization facilities are successfully used for graphical and digital representations of changes in structural dynamic parameters in time and efficiency of different seismic protection systems. This option is very important in the training process as it allows students to focus on those characteristics that are essential for understanding the behavior of the dynamic system under test.

2. Structure of the proposed laboratory

The laboratory is based on a library of structural bridge elements, a library of anti-seismic devices, and a library of seismic loads. The laboratory was developed based on an analysis of the general aspects of seismic protection that are applied in practice to modern bridges [1, 11] and conforms to classifications of international standards [12–14], bridge design specifications [15], and to the scientific and technical publications of manufacturing firms.

The two primary methods of seismic protection are: (a) the protection by energy distribution, where the seismic energy proceeding from the subsoil is distributed to different structural components and thus the accumulation of significant energy is prevented; and (b) the protection by basis isolation and energy dissipation, which reduces the energy applied to the system and the conversion of energy to heat [2].

The fundamental strategies in modern seismic design are period shift and energy dissipation [16]. Period shift reduces the acceleration transmitted to the structure, yet causes increased displacement between the structure and the foundations, or between the structural components. Energy dissipation, in addition to a further reduction of the acceleration, reduces relative displacement. Applying these methods prevents cost-intensive structural stiffening and provides maximum protection for persons and structures.

3. The library of structural bridge elements

The Structural Bridge Elements Library was developed based on an analysis and generalization of schemes of bridges. It allows virtual bridge models with various structural schemes, number of spans with continuous deck or separate span parts as well as suspended bridges to be created. The Structural Element Library shown in Fig. 1(a) contains the blocks required for creating a Simulink bridge model. These blocks contain elementary Simulink

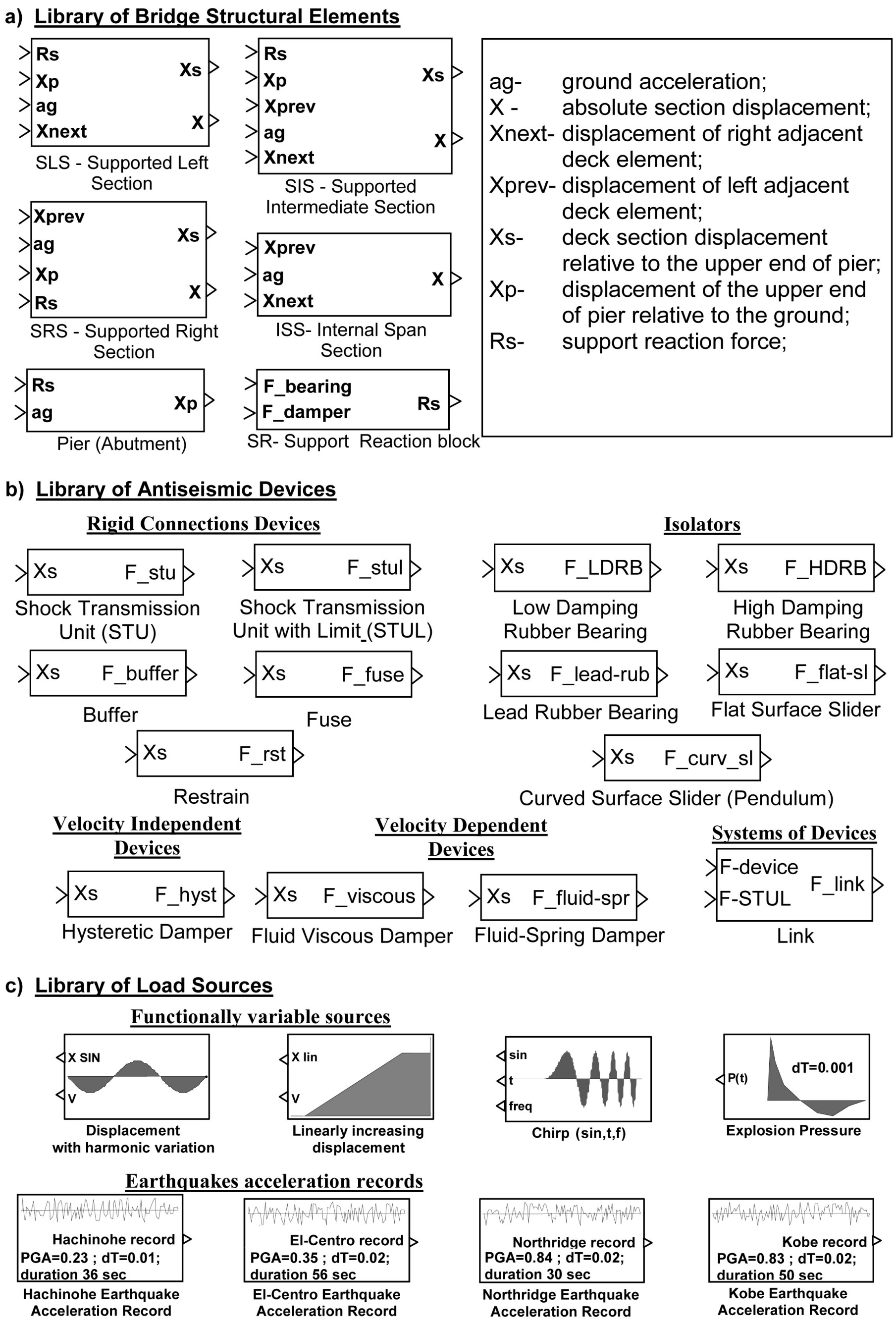

Fig. 1. Contents of the dynamic bridge laboratory library.

blocks (integrators and algebraic blocks) for integrating differential equations of motion. Creating bridge model techniques include the representation of the bridge's deck in the form of concentrated masses (Supported Left, Intermediate, Right Sections and Internal Span Section), connected by interaction forces. The interaction forces are defined by the longitudinal or transverse rigidity of deck and the equivalent viscous damping ratio that may be assumed, based on the material of the members, in which the larger energy part is dissipated during the seismic response [12]. These forces are calculated using a list of block mask parameters, including values of the deck's adjacent parts' stiffness and equivalent viscous damping ratios. The block inputs are adjacent sections' displacements, and the outputs are absolute deck displacements relative to pier base.

The Left, Intermediate, and the Right Supported blocks are used to connect anti-seismic devices. To calculate the forces in the anti-seismic devices, the blocks generate output X_s (bridge displacement relative to pier). The blocks have an input of R_s (device reactions) and work in an R_s feedback mode. To calculate X_s as a difference between deck and pier displacements, the blocks contain X_p inputs being the upper pier end displacement relative to the ground.

The pier is modeled as a one-mass system [12]. The mask parameters of this model's block are stiffness and equivalent damping ratio. The Pier block integrates the equation of motion for a mass moving under seismic action and the forces applied by anti-seismic devices. The pier block can also be used to model right and left abutments by defining appropriate values for mass, and longitudinal and transverse stiffness.

All blocks have an input for applying a ground acceleration signal a_g on the bridge. The Support Reaction block calculates the reaction force, applied to a span section, connected to a bearing. The force is obtained as a sum of forces appearing in bearing and dampers.

The Structural Bridge Elements Library allows students to develop dynamic models and study bridges vibrations in the both longitudinal and transverse directions. In the case of longitudinal vibrations, the stiffness of bridge span elements and piers in longitudinal directions should be defined in their blocks. Dynamic models for transverse bridge dynamics can be developed in a similar manner by defining structural element parameters in the transverse direction. A Simulink model, corresponding to the bridge's physical model, is composed using the library blocks by connecting appropriate input and output ports of the blocks.

4. The anti-seismic device library

4.1 Classification of anti-seismic devices

The Anti-Seismic Device Library was developed to conform to anti-seismic device classifications in modern standards. It can be modified and expanded by new types of devices to reflect emerging scientific knowledge and technical data.

The Anti-Seismic Device Library was designed according to the classifications of European Standard EN15129 [13]. The list of devices is based on analysis of recent scientific and technical publications. It includes devices that have been installed for seismic protection in real bridges [16–21].

There are several elements used to enhance bridge structures behavior under seismic dynamic loadings:

- rigid connections devices: shock transmission unit—STU and STU with protection, restraints with linear behavior;
- velocity-independent devices: hysteretic damper;
- velocity-dependent devices: viscous damper with and without recentering, two-stage viscous damper;
- isolators: low and high damping rubber bearings (LDRB and HDRB), lead-rubber bearing (LRB), sliding isolators, sliding pendulums.

The Simulink Structural Control Device Library, shown in Figure 1(b), was developed, based on analysis of the above listed existing structural control devices. For each control device type a Simulink block was developed according to the device's characteristics. The models are built using existing Simulink libraries alone and have a dialogue window for selecting device parameters. The interface of all Anti-Seismic Devices Simulink blocks has an input X_s (displacement of bridge deck relative to piers), and an output F_{device} (device force). In the case of an Anti-Seismic Device with force–velocity constitutive relations, the velocity, required for calculating the value of F_{device}, is obtained by differentiating X_s by time within the Simulink device model.

Figure 2 shows force–displacement models in characteristic operating modes for some dampers, developed using the proposed Simulink structural control device blocks. These graphs illustrate the control devices performance in seismic protection systems and are used in the teaching process to explain the impact of these devices on the dynamic behavior of bridges.

4.2 Constitutive laws and mathematical models of anti-seismic devices

Simulink models of anti-seismic devices are developed in accordance with their constitutive laws [12,

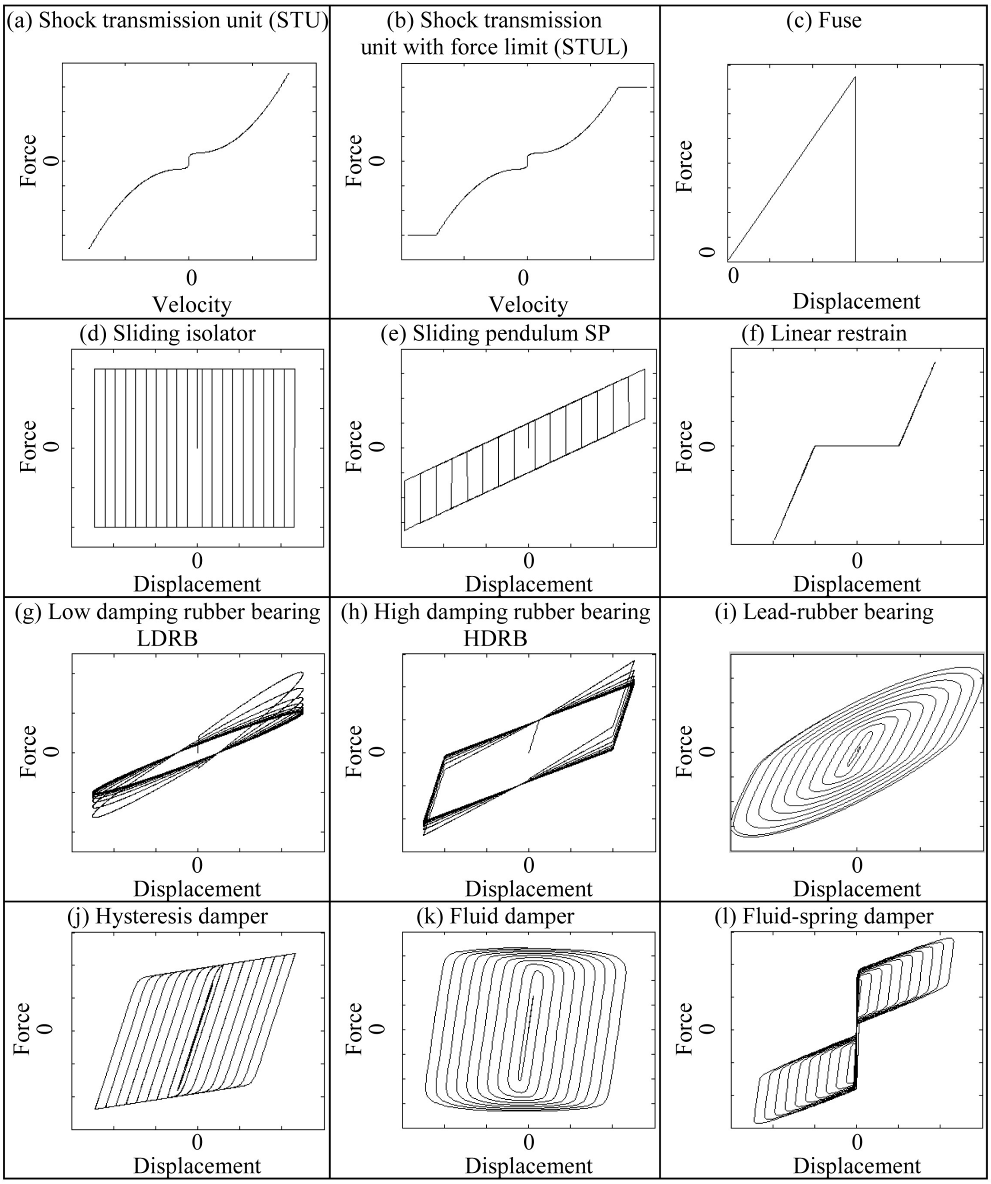

Fig. 2. Typical force–velocity and force–displacement characteristics, obtained using the proposed Simulink structural control device blocks.

13, 22] and results of device testing, published in the scientific and technical literature [20, 21, 23–26].

Hysteretic behavior may be approximated by bilinear *F*–*x* relations with the following parameters:

K_1—elastic stiffness (first branch stiffness),
K_2—post-elastic stiffness (second branch stiffness), and
F_y—yield force under monotonic loading [12–13].

Constitutive laws, shown in Fig. 2, are implemented in the Simulink devices model, based on the hysteretic principle and using a Bouc–Wen mathematical model [24, 27, 28]. The parameters are chosen to achieve linearity of branches in the force–displacement loops [12]. This mathematical model has been implemented in Simulink schemes of hysteretic dampers, lead–rubber bearings and high damping rubber bearings [12]. Parameters K_1, K_2 and F_y are determined by prototype testing [12, 13] by applying ramp and cyclic loading. For lead–rubber bearings, the parameters are defined by properties of rubber and lead core [12].

Behavior of low-damping elastomeric bearing should be approximated by a linear element with corresponding transverse stiffness [12]:

$$K_{eff} = \frac{G_b A_b}{t_b} \tag{1}$$

where G_b is the elastomer's shear modulus, A_b is the effective horizontal area and t_b is the total elastomer's thickness.

The equivalent viscous damping ratio of the low-damping bearing is $\xi < 0.06$ [13]. According to this requirement, the following mathematical model was used to develop a Simulink scheme of elastomeric bearing [24]:

$$F = K_{eff} X_s + C\dot{X}_s. \tag{2}$$

Here C denotes the viscous damping coefficient, determined as follows [24]:

$$C = \frac{K_{eff}\,\xi}{\pi f}, \tag{3}$$

where f is the vibration frequency.

An essential feature in the elastomeric bearings behavior is scragging. Scragged bearings show a significant drop of shear stiffness in subsequent cycles. This effect is prominent mainly in high damping and in low-shear modulus bearings [16, 12, 23]. During the vibration of the bridge under seismic action this phenomenon reduces natural frequencies and damping. To take into account this phenomenon in elastomeric bearings modeling, exponential dependence of K_2 on the number of cycles N can be used [23]:

$$K_{eff} = K_{eff,in} + \left(K_{eff,in} - K_{eff,end}\right)\ \exp(-aN_c), \tag{4}$$

where $K_{eff,in}$ and $K_{eff,end}$ are the initial and final values of post-elastic stiffness, a is the parameter of exponential decrease of stiffness per cycle, and N_c is the number of cycles.

For high damping rubber bearings, the bi-linear model can be adopted using parameters K_1 and K_2. Scragging is taken into account using Equation 4, by replacing K_{ef} by K_2 [2]. Parameters $K_{eff,in}$ and $K_{eff,end}$ or $K_{2,in}$ and $K_{2,end}$ can be obtained based on the results of cycling load test T4, described in Annex K of [12], by bi-linear approximation of the hysteresis loop, taking their values after the 1st and 15th cycles respectively. For example, according to available test results [23], $K_{2,in}$ = 1.2 kN/mm, $K_{2,end}$ = 0.9 ken/mm and a = 0.3.

Constitutive relations of fluid viscous damper behavior, obtained using corresponding mathematical models, conform to recommendations of standards and tests results [20]. It is known that fluid compressibility has a very low effect on the damping ratio, but as fluid compressibility provides certain elasticity, it creates recentering capacity. Consequently, Maxwell's mathematical model [13, 20] was adopted

$$F_v = C\left|\dot{X}_s - \frac{\dot{F}_v}{K_r}\right|^{\alpha} \text{sign}\left(\dot{X}_s - \frac{\dot{F}_v}{K_r}\right) \tag{5}$$

here C is the damping constant, K_r and α are the damper's stiffness and characteristic exponent respectively.

Higher value of the characteristic exponent yields higher recentering capacity.

The constitutive law of a fluid spring damper is obtained by summing the forces, generated by a pre-stressed spring element and fluid pressure [2, 13]. A mathematical model of the device has the following form:

$$F_{vs} = F_v + F_s, \tag{6}$$

where F_v is the force of fluid pressure according to Equation 5 and F_s is the force of a spring with stiffness equal to K_s and loaded by F_0:

$$F_s = F_0\text{sign}\,(X_s) + K_s X_s. \tag{7}$$

Mathematical models given by Equations 5–7 are defined as follows:

- the force of an elastic element is defined by the motion of the stem;
- pressure in the cylinder is defined by a difference of displacements $X_s - F_v/K_r$;
- the force, applied to the stem by a preloaded spring, changes its sign when passing through the central position.

The accepted mathematical model form of the constitutive law for a sliding isolator with curved sliding surface (friction pendulum) is [12, 24]:

$$F = N\frac{X_s}{R} + \mu N\text{sign}\left(\dot{X}_s\right), \tag{8}$$

where N is the force, normal to the sliding surface of the isolator, R is the radius of the sliding surface, and μ denotes the dynamic friction coefficient.

For isolators with a flat surface, $R = \infty$ should be used in Equation 8.

The mathematical model of STU is based on its functional description [2, 12]:

- for low velocity motions ($\dot{X} < V_1$) due to temperature effected creep or shrinkage of the deck, the reaction F_{min} is very low;
- for high velocity motions ($\dot{X} > V_2$) due to seismic action the movement is blocked and the device behaves as a rigid connection. The following values of characteristic velocities can be accepted: V_1 = 0.1 mm/s and V_2 = 1mm/s [12].

A Simulink model of STU is presented as a combination of two parallel fluid devices. The parameters

C_1 and α_1 of the first device are chosen so that the force remains almost constant and equals $F_{\min}$ ($C_1 = 1.4\,F_{\min}$ kN·s/mm and $\alpha_1 = 0.15$). The second device comes into effect when $\dot{X} > V_2$. For achieving rapid force growth with increasing velocity, a damper characteristic exponent $\alpha_2 = 2$ is used. In the model of STUL with limited maximal force, an extra force limiting block is added.

Mathematical models of Restrain, Buffer and Fuse devices are developed according to their functional descriptions [12, 13] and characteristic graphs [29].

4.3 *Simulink models of anti-seismic devices*

An examples of a Simulink-based model of an anti-seismic device for a Fluid–Spring Damper block is presented in Fig. 3. Figure 4 shows a model of a Lead–Rubber Bearing block. Compressibility of the fluid in the first is taken into account by feedback from the output force, divided by the damper's stiffness (shell and liquid) subtracted from the input displacement. Recentering is accomplished by using an additional elastic element with stiffness K_s. The prestressing spring force F_{s0} is achieved by the corresponding blocks in the Simulink model. For fluid dampers without recentering, stiffness K_s and prestressing F_{s0} are set equal to zero.

According to the design and the rheological features of the lead–rubber bearings' constituent components, the following models are combined in its Simulink model:

- the lead core model, operating in elastic and plastic ranges according to the hysteretic damper *F*–*x* characteristics (Fig. 2(j)), based on the Bouc–Wen hysteretic model [24, 27, 28];
- the Kelvin model of viscoelastic material, according to *F*–*x* characteristics of a viscoelastic damper (Fig. 2(g)).

The scragging effect is not included since its effect is

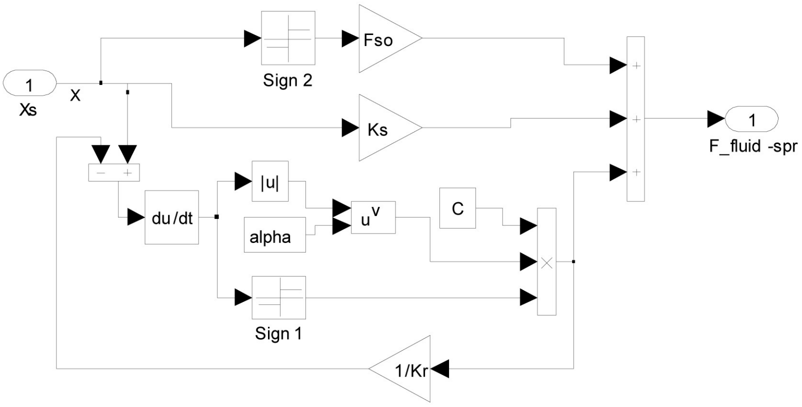

Fig. 3. Simulink scheme of fluid–spring damper with recentering.

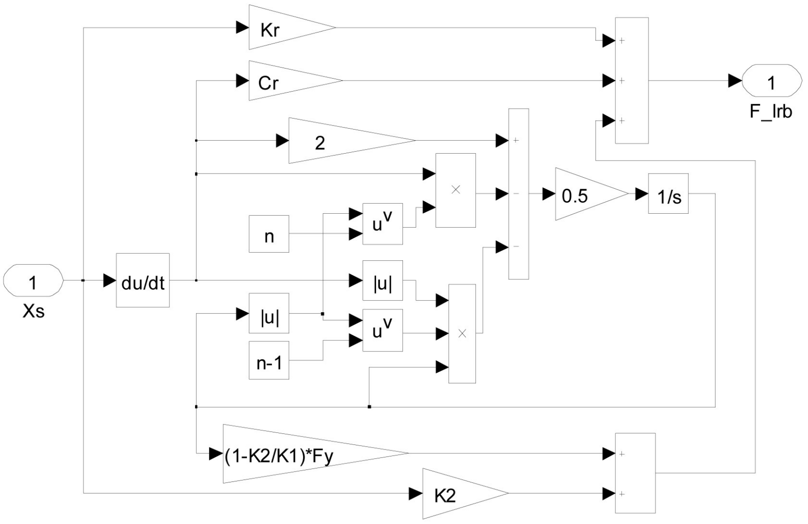

Fig. 4. Simulink scheme of lead–rubber bearing device.

negligible, compared with the core rigidity. The lead–rubber bearing force is calculated as a sum of forces, created by both models (Fig. 2(i)).

To study the longitudinal or transverse vibrations of a bridge, appropriate anti-seismic devices should be chosen and corresponding characteristics should be defined as their Simulink blocks parameters.

5. Application of loading

The model allows application of seismic (earthquake or underground explosion) and harmonic loads. For this purpose, the structural elements blocks interface have an input base acceleration port a_g. Loads may be selected from a list of standard Simulink source blocks [30] (like sinusoidal, ramp, repeating sequence, etc.) or from the Seismic Loads Library, originally developed by the authors (Fig. 1(c).), which contains the source blocks of ground acceleration records, the acceleration source due to underground explosion and the modified chirp source. Since Simulink enables one to change the simulation time step, the analysis is performed with a fixed time step, which is selected according to the step of the input ground acceleration record and provides the desired simulation accuracy.

6. Conducting laboratory works

6.1 The structure of laboratory works

Laboratory works are performed according to the task in which the bridge scheme, deck spans lengths and cross-sections, pier's mass and stiffness, seismic isolation devices types and parameters as well as schemes of their arrangement are specified. Furthermore, design displacement of the base isolation system d_{cd} [12], peak ground acceleration a_{gR}, and design ground acceleration a_{g} are specified.

Each laboratory work is performed in four stages:

1. the preliminary stage,
2. the fundamental mode spectrum analysis,
3. the nonlinear time-history analysis, and
4. the final analysis stage.

The second and third stages are performed according to the EN1998 Standard requirements [12, 14].

The preliminary stage includes:

- familiarization with the characteristics of the base isolation devices used;
- calculation of the upper and lower design properties of devices (UBDP and LBDP); the parameters' variability is defined according to [12] (see Chapter 7.5.2.3);
- calculation of the devices' effective stiffness and energy dissipation as well as finding the entire isolation system's effective stiffness, effective damping, and effective natural vibration period [12].

The second stage includes calculation of the displacement in the isolation system and maximal forces in isolators.

The third stage includes:

- construction of a bridge model using the Structural Elements Library blocks and putting together a seismic isolation system using the Control Devices Library blocks;
- connection of visualization devices in order to record the required characteristics, such as forces in bearings and dampers, viscous damper stock velocity, deck, pier and bearing displacements;
- spectral analysis and finding the fundamental natural frequency of the bridge by applying a harmonic acceleration signal with a linearly increasing frequency using the Simulink chirp signal source;
- time-history analysis under earthquake acceleration records. This modeling is performed for upper and lower bound values of anti-seismic devises' parameters.

The fourth stage is the analysis of results which includes:

- comparison of the results obtained using modal spectrum and time-history analyses;
- comparison of functional parameters of anti-seismic devices (maximum allowable values of force, velocity and displacement) with the results of time-history analysis;
- drawing conclusions and making recommendations to change the system scheme and parameters of anti-seismic devices.

6.2 The impact of the proposed method on teaching and learning

The advantages of using Simulink in teaching and learning becomes evident at the first, third and fourth stages. At the first stage using Simulink models enables to learn the force–displacement and force–velocity behavior of different anti-seismic devises.

Creating a Simulink model of a bridge yields deeper understanding of the function of each bridge component, kinematic and force interaction between the bridge elements as well as between the elements and control devices. By connecting visualization devices, students gain their knowledge of the physical nature of kinetic and force parameters that require visualization. By performing spectral analysis and finding the fundamental natural frequency of the bridge, students obtain a physical understanding of mode shapes and frequencies of a continuous multi-supported structure.

Time-history analysis under earthquake acceleration records and comparison of the results of modal spectrum and time-history analyses students obtain information on the bridge elements' movement due to stochastic earthquake loading. Analysis of the control devices' influence on the bridge vibration enable students to reach conclusions regarding the bridge's dynamic response's dependence on the type and parameters of the devices.

The possibilities of applying the proposed method are limited due to the time planned for each laboratory work and the complexity of the real structure to be analyzed. In other words, for a complex bridge with many supports, different control devices that have various parameters yield a complex Simulink model that requires a relatively long time to create using the developed libraries and further analysis. Using different control devices with various parameters decreases the efficiency of the laboratory, as it is more difficult to understand the role of each device.

The above-mentioned disadvantages can be overcome by creating a next generation of the virtual laboratory, in which the structure elements library will include more complex blocks (one-, two- or multi-bay structures) and the control devices library will contain blocks of control devices (bearing + damper + STU [17, 18]).

7. Example: Analysis of LDRB and fluid viscous dampers efficiency

7.1 Design scheme, dynamic and Simulink models of a bridge

To demonstrate the efficiency of the proposed method, the dynamic behavior of a real bridge subjected to the El Centro earthquake with peak ground acceleration scaled to 0.2g was analyzed. A general view of a railway bridge, used in the frame of the current example, is shown in Fig. 5. A cross section of the bridge is presented in Fig. 6. The properties of the main bridge elements are given in Table 1. The bridge comprises a continuous deck, supported by four piers.

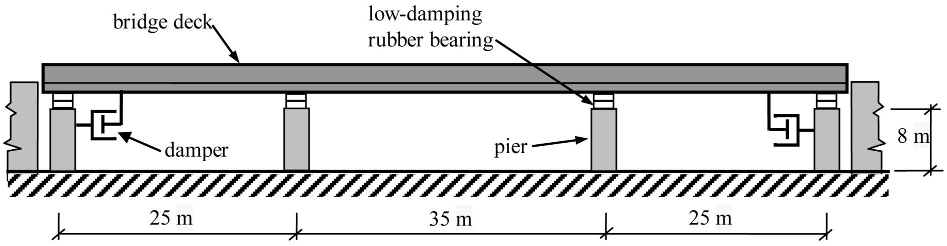

Fig. 5. A three-span bridge model with base isolation and dampers.

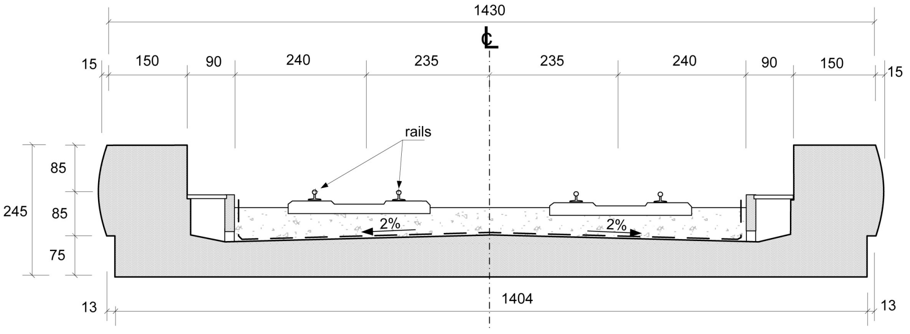

Fig. 6. The bridge deck cross section (cm).

Table 1. Properties of the bridge components

Properties	**Deck**	**External piers**	**Intermediate piers**
Cross section area (m^2)	15.42	5 × 0.64	10 × 1.54
Moment of inertia I_y (m^4)	391.6	5 × 0.032	10 × 0.189
Elasticity modulus (GPa)	37	35	35
Mass per unit length (ton/m)	53	5 × 1.6	10 × 3.85

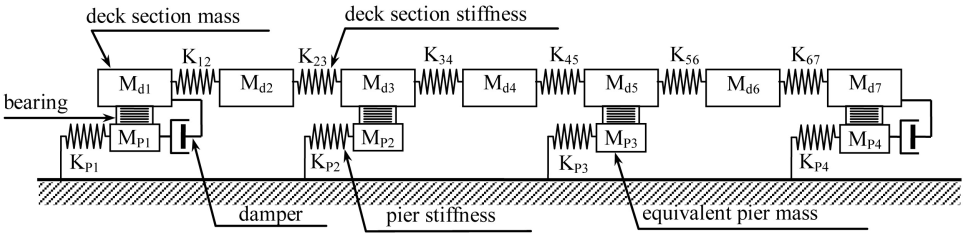

Fig. 7. Dynamic model of seismic isolated three-span bridge.

Table 2. Parameters of the bridge dynamic model

Deck			**Piers**		
Section mass (ton)	**Stiffness in longitudinal direction (GN/m)**	**Stiffness in transverse direction (GN/m)**	**Pier equivalent mass (ton)**	**Stiffness in longitudinal direction (GN/m)**	**Stiffness in transverse direction (GN/m)**
$M_{d1} = 331$	$K_{12} = 45.6$	$K_{12} = 89.1$	$M_{P1} = 450$	$K_{P1} = 1.0$	$K_{P1} = 2.0$
$M_{d2} = 662$	$K_{23} = 45.6$	$K_{23} = 89.1$	$M_{P2} = 550$	$K_{P2} = 3.0$	$K_{P2} = 6.0$
$M_{d3} = 794$	$K_{34} = 32.6$	$K_{34} = 32.5$	$M_{P3} = 550$	$K_{P3} = 3.0$	$K_{P3} = 6.0$
$M_{d4} = 926$	$K_{45} = 32.6$	$K_{45} = 32.5$	$M_{P4} = 450$	$K_{P4} = 1.0$	$K_{P4} = 2.0$
$M_{d5} = 794$	$K_{56} = 45.6$	$K_{56} = 89.1$			
$M_{d6} = 662$	$K_{67} = 45.6$	$K_{67} = 89.1$			
$M_{d7} = 331$					

The external piers are represented by five columns (height 8 m and 0.9 m in diameter) and the intermediate piers by ten columns (height 8 m and 1.4 m in diameter). The columns are connected by a continuous beam (1.2 m in height).

The dynamic model of the bridge is shown in Fig. 7. It includes a seven mass deck model and four single mass pier models. The parameters of the dynamic model are given in Table 2. The damping ratio of the bridge deck and piers was assumed to be 5% [12].

A Simulink scheme, corresponding to this dynamic model, is presented in Fig. 8. It is created using the above described library blocks for bridge structure elements and anti-seismic devices. The Simulink scheme mask parameters are defined as parameters of the dynamic model. For visualization of the measured parameters Scope blocks are used. Graphs of several measured parameters are presented on a common axes system using the Simulink Mux block.

According to displacements of each mass relative to another and the stiffness of the bridge deck elements between the masses, the elastic forces are calculated in the Section library block. As the interaction forces between pier and deck are defined by a relative displacement between these elements, the X_p output, representing the deck displacement relative to the ground, is connected as a feedback to the Section block. In a similar way the output R_s, representing the interaction forces between pier and deck, is also connected to the Section block.

The Simulink scheme is used to study the bridge dynamics in the following modes:

- rigid connection between deck and pier (stiffness parameter in the LDRB block is assumed to be 100 times higher than that of the pier and the viscous damper damping constant is selected to be equal to zero);
- with LDRB (at zero value of viscous dampers damping constant);
- with additional viscous damper connection.

The bridge's natural frequencies and mode shapes can be determined in each direction, substituting corresponding stiffness parameters. Further discussion in the frame of this study will be performed for the bridge in the X direction only. For calculating the bridge natural frequencies a harmonic excitation with a linearly growing frequency (chirp signal) is used, as shown in Fig. 9. Using the graph, the actual time at maximum response is obtained and, according to the time, the frequency value, corresponding to the natural vibration frequency is found. Displacements at that instant of time, corresponding to maximum response, give the bridge mode shape.

7.2 Dynamic analysis of the bridge

Following Fig. 9, the displacements of piers at each time instant are equal. This means that, with the assumed pier stiffness, the deck's dynamic behavior corresponds to that of a rigid body. The results of dynamic analysis are summarized in Table 3. Following Table 3, the dominant natural vibration

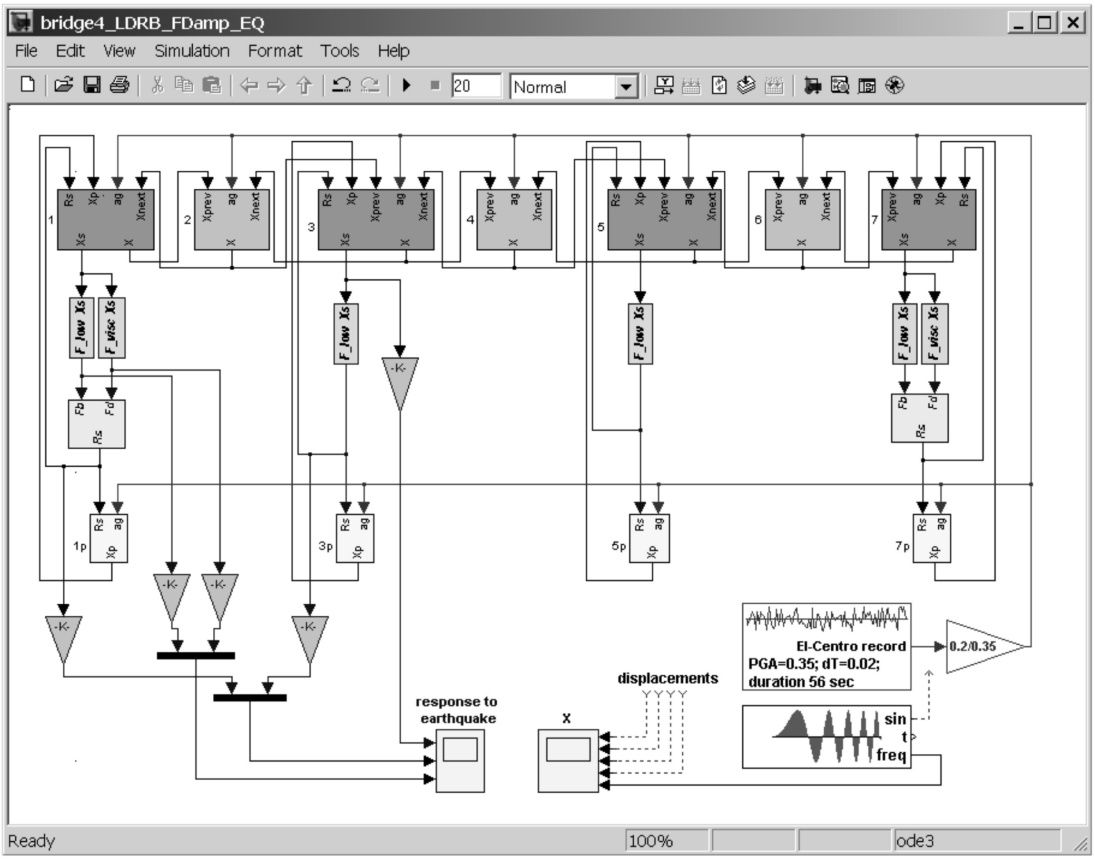

Fig. 8. Simulink scheme of a three-span bridge model with lead–rubber bearings and viscous dampers.

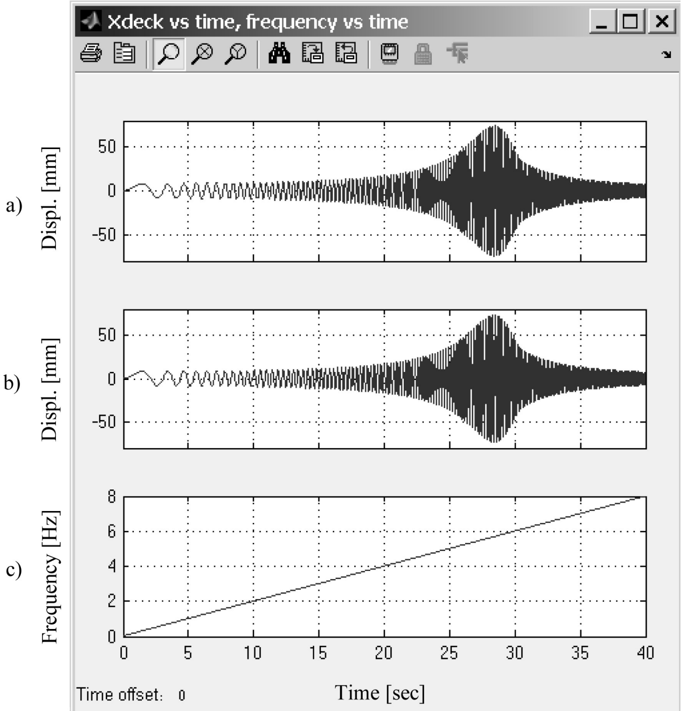

Fig. 9. Non-isolated bridge response to harmonic acceleration with linearly increased frequency (chirp signal): (a)–(b) time-history of external and internal deck sections displacements at piers 1 and 2 (mm); (c) load frequency vs. time.

Table 3. Bridge dynamic parameters, obtained by testing Simulink models

	Non-isolated bridge	**A bridge with LDRB**	**A bridge with LDRB and viscous dampers**
Natural frequency, Hz	5.6	0.431	0.428
Peak pier displacement, mm	3.3	1.2	1.2
Peak deck displacement relative to pier, mm	0	125	72
Peak force at the intermediate pier, MN	7.45	1.42	0.95
Peak force at the external pier, MN	1.56	0.71	0.67
Peak force in the LDR bearing at the intermediate pier, MN	—	1.42	0.95
Peak force in the LDR bearing at the external pier, MN	—	0.71	0.47
Peak force in viscous damper, MN	—	—	0.24

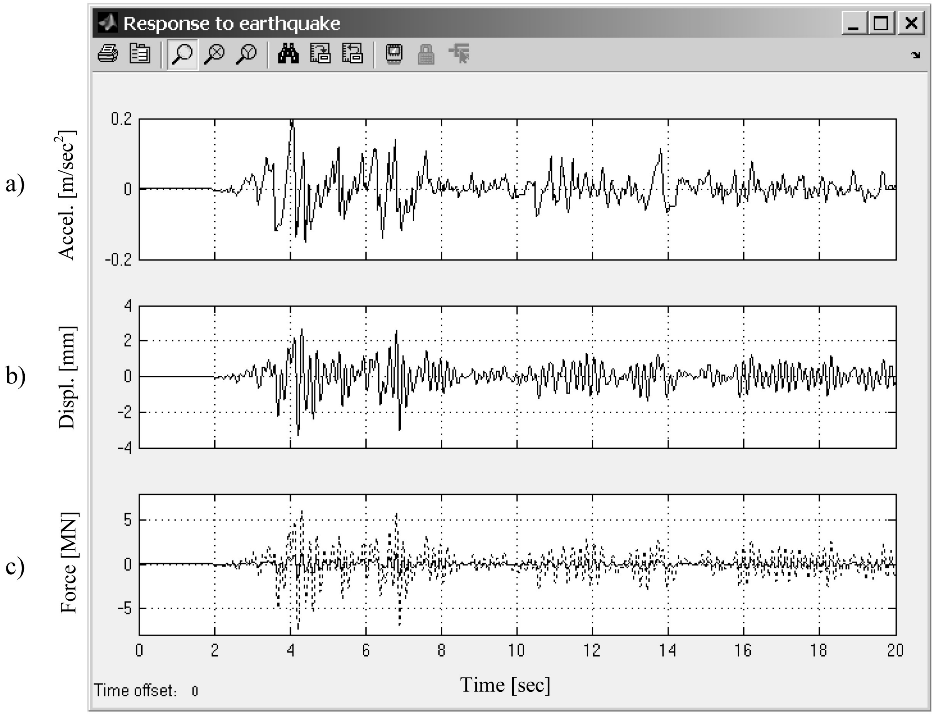

Fig. 10. Response of non-isolated bridge to El Centro earthquake: (a) ground acceleration; (b) displacement of the deck relative to the ground (mm); (c) forces at intermediate pier (dashed line) and at external pier (solid line).

frequency of the fixed based bridge corresponds to that of free vibration of its deck as a rigid body with a total mass of the deck and piers, and total stiffness of all piers.

Displacements and forces at external and intermediate piers with rigid deck connections, due to earthquake, are presented in Fig. 10. As it follows from this figure, due to relatively high stiffness of the piers, the general character of the deck motion conforms to the earthquake accelerogram. Additional parameters of this motion regime are presented in Table 3.

The parameters of LDRB were selected according to recommendations given in [2]: diameter—500 mm, stiffness—15.4 MN/m, limit displacement—81 mm. 5 and 10 LDRB were placed at each external and internal pier, respectively. As the bearings' stiffness is much lower than that of the piers, the dominant natural frequency, obtained by chirp test, is defined by the bearings' stiffness and it is about 13 times lower than in case of a fixed base deck (Table 3).

Response of the base isolated bridge to the same earthquake is presented in Fig. 11. The deck vibration is characterized by its natural vibration frequency and variable amplitude.

The forces acting on each pier are decreased 5 and 2 times for internal and external piers, respectively. The peak deck displacement relative to the pier (125 mm) significantly exceeds the limit displacement value that was selected (81 mm), therefore, according to [2], supplemental dampers should be added.

As the deck has high stiffness in its plane, its displacements relative to the piers can be taken as

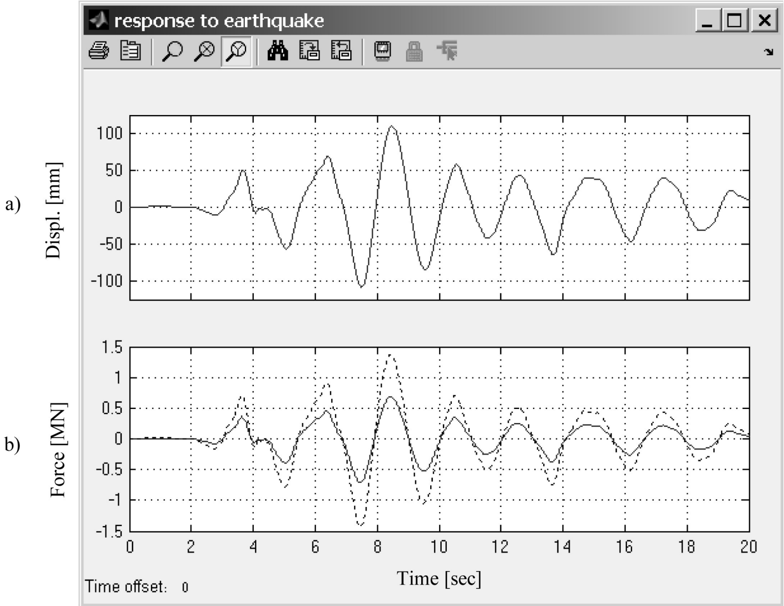

Fig. 11. Response of the base isolated bridge to El Centro earthquake: (a) displacement time-history of the deck relative to the pier, (b) force at the top of the intermediate pier (dashed line) and at the top of the external pier (solid line).

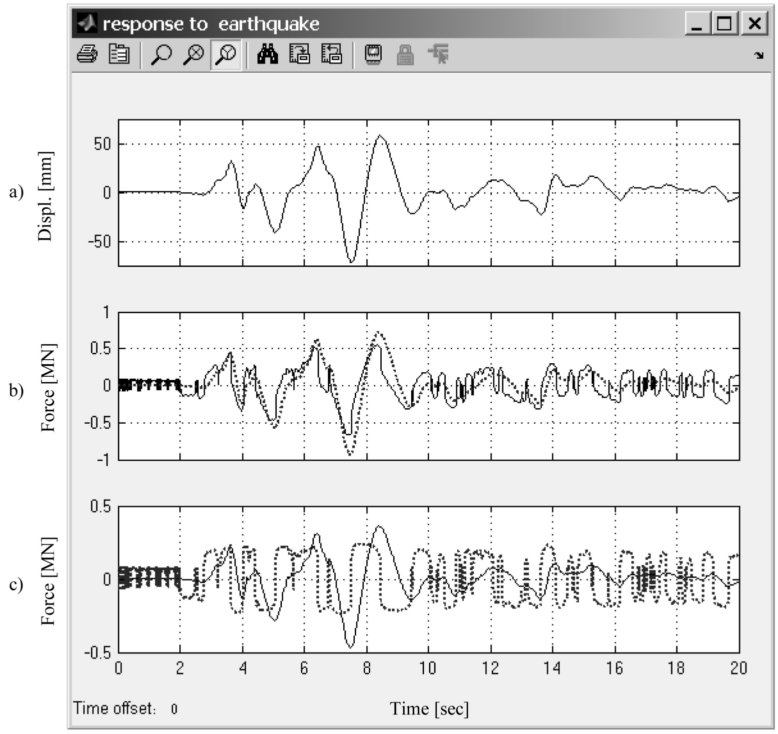

Fig. 12. Response of the bridge with LDRB and viscous dampers to El Centro earthquake: (a) displacement time-history of the deck relative to the pier, (b) force at the top of the intermediate pier (dashed line) and at the top of the external pier (solid line); (c) forces in viscous damper (dashed line) and in LDRB (solid line).

for a rigid body. Therefore, a scheme with two viscous dampers, connected between the deck and external piers, is assumed. The dampers' property parameters were selected according to commercially available devices: cylinder diameter 170 mm, stroke ±100 mm, peak damping force 300 kN, damping constant 250 kN/(m/s)$^{0.15}$.

The response of the base isolated bridge with viscous dampers to the El Centro earthquake is presented in Fig. 12. The nature of the deck motion is similar to the previous case (without dampers), but displacements have lower amplitudes.

Following the modeling results shown in Table 3 and, as was expected, adding viscous dampers yields practically no changes in the dominant natural vibration frequency and allowed:

- decreasing the deck displacement relative to the piers about 1.7 times;
- decreasing the dynamic load on the internal pier about 1.5 times.

The deck's displacement relative to the piers is below the limit displacement value of LDRB and the viscous dampers' stroke (see Table 3). The peak forces in viscous dampers are also within the permitted limits.

In a similar way, the bridge vibrations in the perpendicular direction can be modeled. After that the bridge response to other earthquake motions is obtained. If required, based on simulation results, LDRB and viscous dampers parameters are corrected.

8. Conclusions

A virtual laboratory system for studying the dynamic behavior of bridges was developed. It allows the selection of methods and devices for vibration control. The system is presented in the form of libraries of bridge structural elements, anti-seismic devices, and seismic loads.

The laboratory allows:

- the study of the functional characteristics of control devices and dependencies of their performance on their technical parameters;
- the investigation of the bridges' dynamic behavior under various types of exposure, depending on the control devices' types and parameters;
- the performance of time-history analysis according to the Standards' requirements.

The virtual laboratory offers the following advantages:

- the construction of bridge models with various geometry, number of spans and combinations of control devices;
- the structural control devices library can be modified and expanded by new types of devices to reflect emerging scientific knowledge and technical data.

The proposed virtual laboratory enables students to improve the learning process and its outcomes in the field of bridges dynamics. It extends students' understanding of dynamic problems and ways for enhancing a bridge's seismic response by modeling dynamic processes and visualizing their parameters in an easily comprehensible format.

It should be mentioned that the possibilities of applying the proposed method in the present form are limited due to the time available for each laboratory work and the complexity of the real structure to be analyzed. These drawbacks can be overcome by using blocks of more complex structures and the control devices that will be used in the next generation of the virtual laboratory.

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