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VIBRATION MITIGATION IN BRIDGES USING INTEGRATED SEMI-ACTIVE CONTROL CONCEPTS

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Abstract

Passive control is extensively used in bridges today for mitigation of seismically induced vibrations mostly due to its low cost to effectiveness ratio. Passive control is, however not always applicable and active or semi-active control concepts have to be used especially in large bridges. Semi-active control means that certain key parameters of the control device in a system like friction or flow of magnetorheological fluid are controlled. It offers the possibility to further improve the seismic performance of bridges with little additional effort, especially in large bridges where the low maintenance costs are a major advantage of semi-active control when comparing to active control.

Except for the mitigation of seismically induced vibrations in bridges, semi-active control can also be used for mitigation of vibration coming from other sources. One example for this is the use of semi-active TMD-s in pedestrian bridges that enable more slenderness and lower construction cost for these bridges. This shows that semi-active control could be also used as integrated vibration mitigation control for not only earthquakes but also wind and traffic induced vibrations.

In order to test the effectiveness of different integrated semi-active control strategies a test setup has been built at the University of Kassel. It consists of a cylinder that is connected to a movable steel construction underneath a semi-active device, which represents a single DOF of the structure. The constraint to just one DOF is not limiting because through the use of hybrid simulation this DOF and with it the semi-active device can be moved to any feasible location in a numerical model of the bridge. The semi-active device can be frictional, magnetorheological or any other.

In the first step it is important to validate the feasibility of hybrid simulation in semi-active control development. In order to do this the results of hybrid simulation experiments will be compared to a real world shaking table tests conducted at IZIIS Skopje. The tested bridge was a scaled down model of a deck bridge with two piers on which UHYDE-*fbr* devices were placed in order to simulate different passive devices. UHYDE-*fbr* device is a patented semi-active bi-directional friction device. The friction force in the device is controlled through the change of air pressure in the device chamber. The same device as in the shaking table experiments will be used in the hybrid simulation experiments for comparison.

Research will further concentrate on developing different semi-active control strategies for bridges. Different control algorithms like H2/LQR algorithms will be tested on the existing numerical model of the tested bridge and also on the ASCE Cape Girardeau benchmark cable-stayed bridge model. The final goal is to develop integrated semi-active control concepts and a hybrid simulation environment for the testing of the developed concepts. First results and conclusions of this on-going research will be presented.

Keywords: semi-active control; hybrid simulation; validation of test results; friction device; large bridges

1. Introduction

Semi-active control of bridges offers a middle way between passive control, which is easily implementable but lacks adaptability and active control, which can be better optimized but is more expensive and less robust [1,2]. Semi-active control means that certain key parameters of the control device in a system like friction or flow of magnetorheological fluid are controlled. Since these devices do not input any energy into the system, they are inherently more stable then active devices [7]. It offers the possibility to further improve the seismic performance of bridges with little additional effort, especially in large bridges where the low maintenance costs are a major advantage of semi-active control when comparing to active control. Although it requires external energy sources, the energy needed is significantly less then that used by active devices. That is why it can use local energy sources like preinstalled batteries and is robust to possible energy grid failures during large earthquakes.

Primary use of semi-active control is mitigation of seismically induced vibrations but it also can be used to reduce the vibrations coming from other sources, like wind and traffic [4,5]. These dynamic loads can cause excessive vibrations and are often the primary limiting factor in building large span bridges. In this sense, semi-active control has the potential to enable to build more slender and cost-effective structures and achieve bridge spans that go beyond those in use today.

Many numerical studies have been conducted to test the effectiveness of semi-active control on large bridges. They usually concentrate on validated numerical models like the ASCE Cape Girardeau benchmark cable-stayed bridge model [6]. An overview of recent advances in structural control is given in [7]. The authors state that in order to achieve practical use of structural control, experimental studies are necessary. The cost-effective alternative to full-scale testing is hybrid simulation that enables the connection of the experimental setup of the semi-active device with the numerical model of the whole structure.

2. Hybrid simulation setup

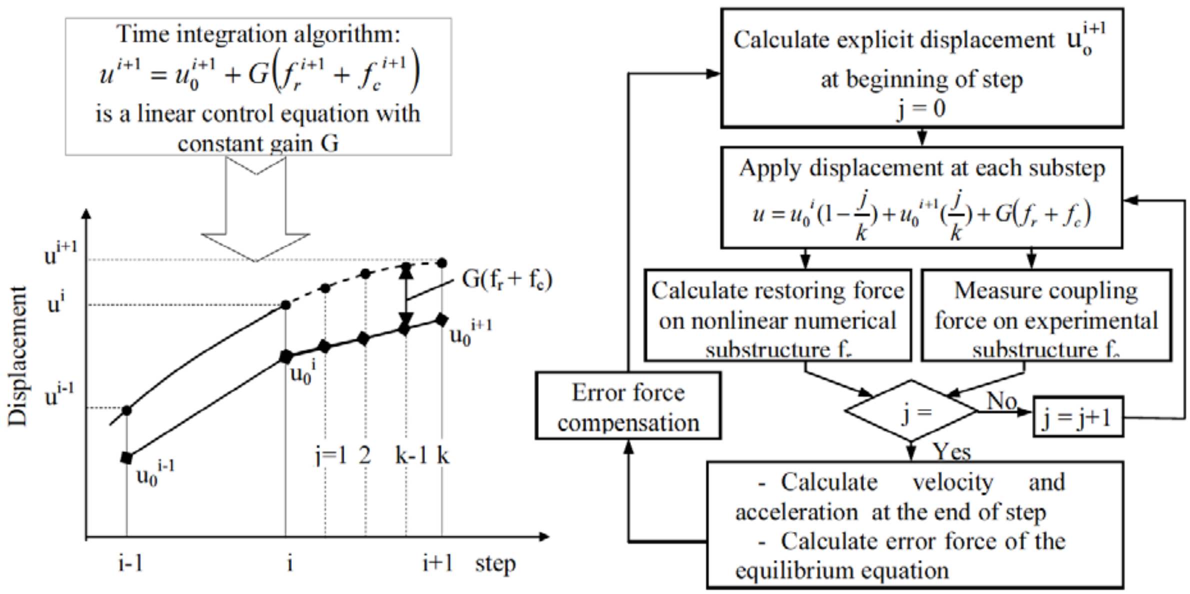
One of the most versatile algorithms for hybrid simulation is the Substep force feedback (Subfeed) algorithm developed by Dorka [8,9,10,11,12,13]. This algorithm was further developed for the use with large numerical models by Obon Santacana [14] and will be used in conducting hybrid simulation tests. In contrast to predictor-corrector methods, this algorithm does not rely on linear models to predict the substructure behavior and then correcting the error in the process of time integration. Instead, the Subfeed algorithm relies only on the measured data to obtain the response of the subsystem. This can be achieved in a digital fashion by using a sub-stepping technique.

The displacement vector u^{i+1} of the numerical model at the next step is split into an explicit and implicit part and described as a linear control equation Eq. (1).

$$\mathbf{u}^{i+1} = \mathbf{u}_0^{i+1} + \mathbf{G}\left(\mathbf{f}_r^{i+1} + \mathbf{f}_c^{i+1}\right) \tag{1}$$

where $\mathbf{u}_0^{i+1}$ is a vector of explicit displacements that are known at the beginning each step, $\boldsymbol{G}$ is the gain matrix, $\mathbf{f}_r^{i+1}$is the vector of nonlinear numerical forces and $\mathbf{f}_c^{i+1}$ is the vector of coupling forces that are measured on the specimen.

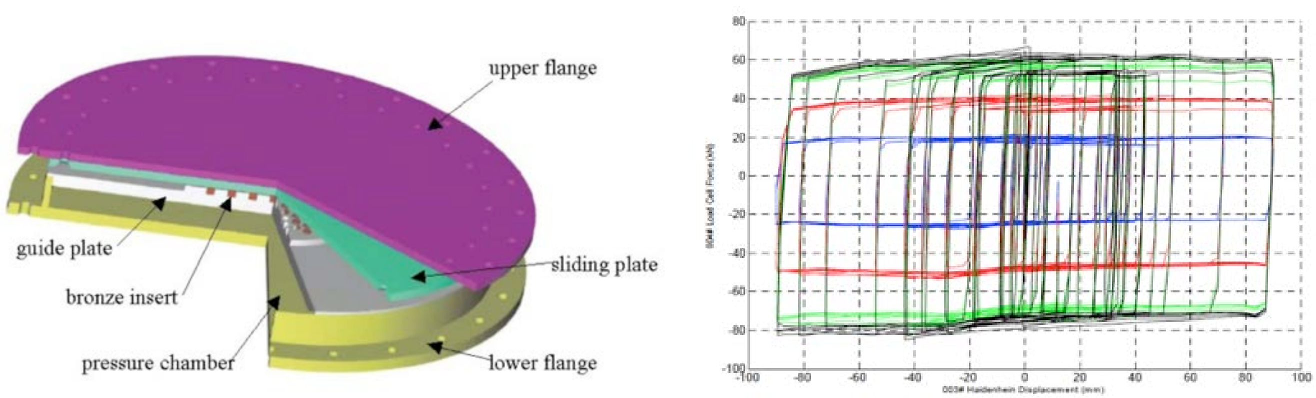
The non-linear numerical forces, f_r and the currently measured coupling forces, f_c are fed back at the sub steps, which are equally distributed over the time step (Fig.1a). At the end of each step, the equilibrium error is calculated and the error force is identified. The error force is compensated at the beginning of the next time step (Fig.1b) by the use of a PID compensator [8] or adaptive force compensation as proposed in [15].



a) Linear control mechanism b) Flow chart of the *Subfeed* algorithm

Fig. 1 - Subfeed algorithm with digital feedback and error force compensation [11,13]

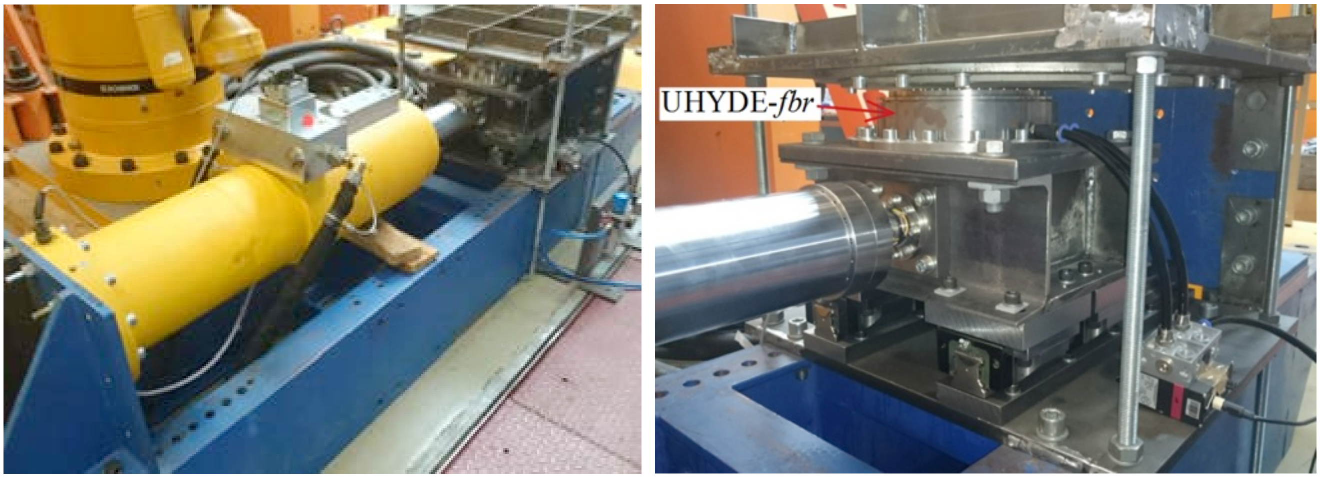
The UHYDE-*fbr* (Fig.2a) device is a patented semi-active air pressure controlled device that can be used for the mitigation of the structure response during an earthquake [16]. By varying the air pressure in the chamber the friction force on the contact surface of the upper flange and the copper inserts of the device is controlled. If the air pressure and, consequently the friction force are held constant, the UHYDE-*fbr* shows almost ideal elastoplastic behavior (Fig.2b). The air pressure can also be changed as a function of displacement, velocity or acceleration and the device can be used to replicate the behavior of various passive devices [17]. In order to get the best results in mitigating the vibration in the structure it is best to vary the pressure according to a predetermined semi-active control algorithm that can be programmed to best suit a specific use [18].



a) Schematic representation b) Hysteresis loops for constant pressure of 2 (blue), 4 (red), 6 (green) and 7 (black) bar

Fig. 2 – Patented bi-directional semi-active friction device UHYDE-*fbr* [17]

In order to test semi-active control concepts for bridges using hybrid simulation a new experimental setup has been built (Fig.3). The setup consists of a base shown in blue in Fig.3a. On one end of the base a hydraulic actuator (shown in orange in Fig.3a) is attached. The piston is connected to a moving steel structure through a load cell. Movement of this steel structure and the lower flange of the UHYDE-*fbr* is enabled through its connection to runner blocks that are placed on rails. The upper flange of the UHYDE-*fbr* is connected to a stationary steel plate.



a) Experimental setup with the base and the hydraulic actuator

b) Part of the setup with the UHYDE-*fbr* device

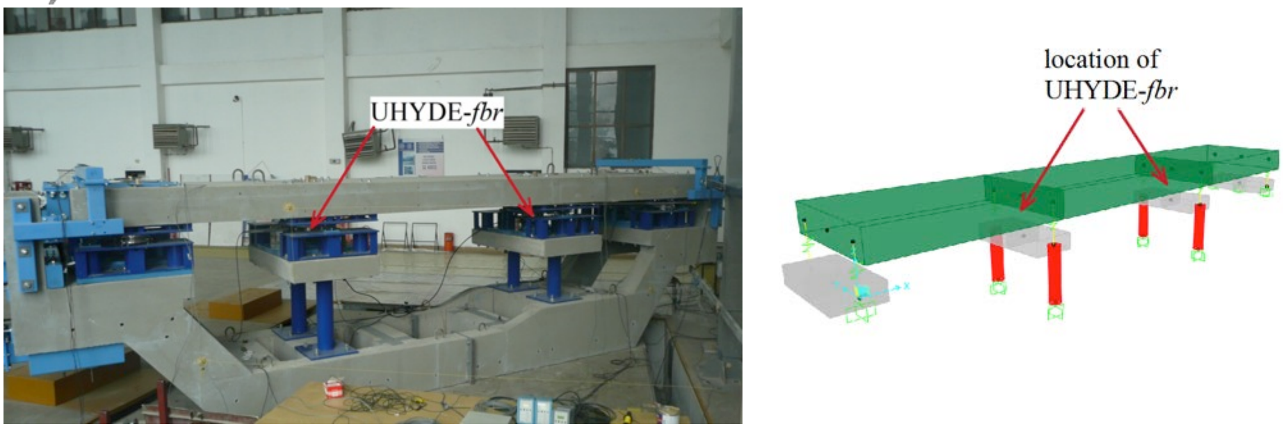
Fig. 3 - Experimental setup in the structural laboratory of University of Kassel

Displacements and accelerations of steel structure as well as the force exerted by the actuator can be measured. The displacement is measured by a LVDT placed directly in the actuator and the acceleration is measured by an accelerometer placed on the movable steel structure. The connection of the piston of the hydraulic actuator and the movable steel structure is accomplished through a load cell. This enables to directly measure the friction force exerted on the connection of the copper inserts and the upper flange of the UHYDE-*fbr*.

By using the described device and a numerical model of a bridge hybrid simulation of the behavior of the bridge system with the installed UHYDE-*fbr* can be conducted. Through a series of data acquisition systems and computers the experimental substructure of the semi-active device can be connected to a numerical model of a bridge. The connection is accomplished through the Subfeed algorithm by inputting the measured force to the numerical model and applying the calculated displacement on the experimental substructure. The UHYDE-*fbr* is the experimental substructure and the actuator can reproduce a movement of a single degree of freedom (DOF) in a numerical model that relates to the desired position of the device in the bridge. The constraint to just one DOF is not limiting because through the use of hybrid simulation this DOF and with it the semi-active device can be moved to any feasible location in a numerical model of the bridge. The tested semi-active device can also be changed to a magnetorheological or any other.

3. Conducted experiments

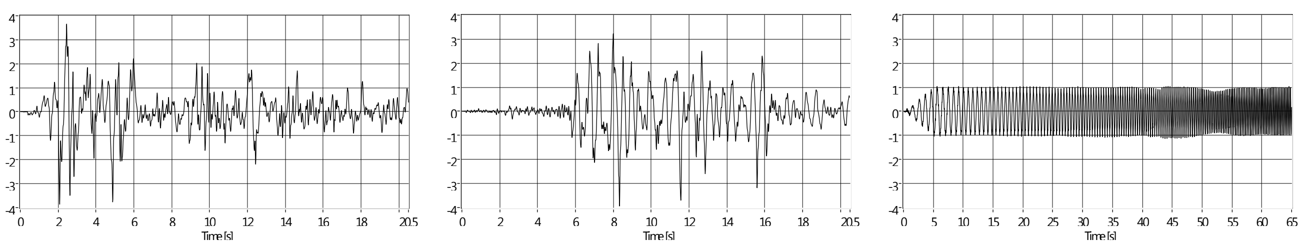
It is important to validate the feasibility of hybrid simulation in semi-active control development through comparison of the results of hybrid simulation experiments to the results of real world reference tests. The reference tests that are used for this purpose are the shaking table tests conducted at IZIIS Skopje during the ISUbridge project within the NATO Science for Peace and Security Program [11]. Within that testing campaign UHYDE-*fbr* devices were used to simulate the behavior of various passive devices on the connection between the piers and the deck in a scaled model of a deck bridge with great success (Fig.4a). The same UHYDE-*fbr* is used in the new experimental setup.



a) Shaking table model of a deck bridge b) Graphical representation of the numerical model

Fig. 4 - Scale model of a bridge with the installed UHYDE-*fbr*

A numerical model of this bridge has been prepared (Fig.4b) and will be used for the hybrid simulations. One of the UHYDE-*fbrs* is numerically simulated as a biaxial Bouc-Wen model [18] and the other is the experimental substructure in the hybrid simulation test. Initial tests with the air pressure in the UHYDE-*fbr* held constant at p = 3 bar were conducted. The same three ground motion records as in the IZIIS testing campaign were used – El Centro (1940) at 140%, Ulcinj-Albatros (1979) at 160% and sine sweep (PGA = 1 m/s^2) in the range from 1 to 4 Hz. These ground motions were inputted under the angle of 45° relative to the bridge longitudinal axes in both hybrid simulation and shaking table tests. Fig.5 shows the acceleration time histories recorded on the shaking table used in the ISUbridge project. These recorded ground motions were used in the hybrid simulation tests.

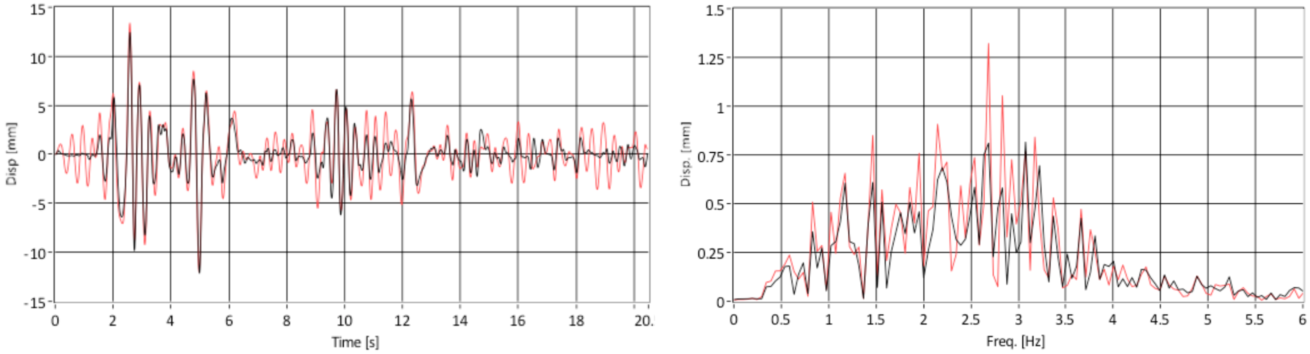


a) El Centro (1940) 140 % b) Ulcinj-Albatros (1979) 160 % c) Sine sweep (PGA = 1 m/s^2) 1-4 Hz

Fig. 5 – Acceleration time histories recorded on the shaking table

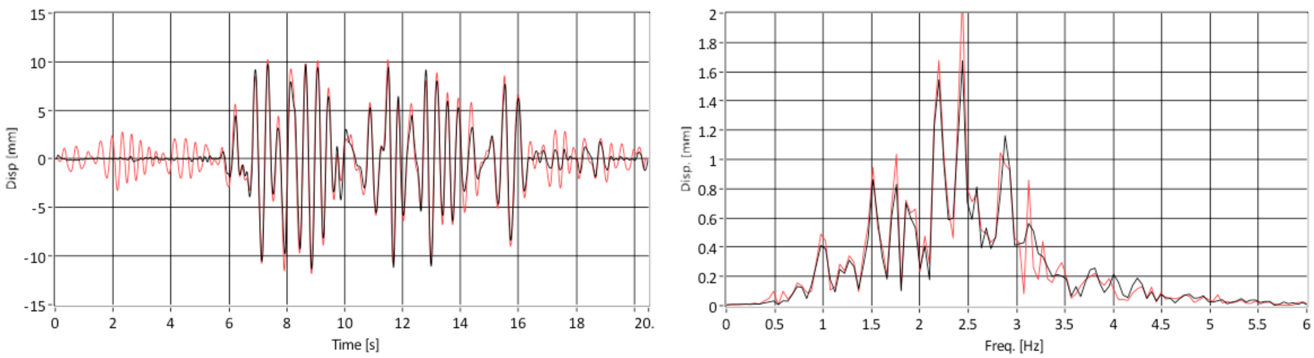
Fig.6, Fig7. And Fig.8 show the relative displacement between the deck and the top of the pier in the transversal direction on the first pier for all three ground motions acquired through shaking table tests (black) and through hybrid simulation tests (red) in time and frequency domain respectively

The recorded relative displacements between the piers and the slab acquired in the hybrid simulation tests show very good overlap with the displacements recorded in the shaking table experiments in time and frequency domain. The recorded peaks in the time domain show an almost perfect match in amplitude. It can also be seen that vibrations with low amplitudes appear in the numerical model where there are none in the shaking table experiments. Vibrations with low amplitudes are the main reason for higher amplitude discrepancies in the frequency domain. The cause of such behavior is under investigation.



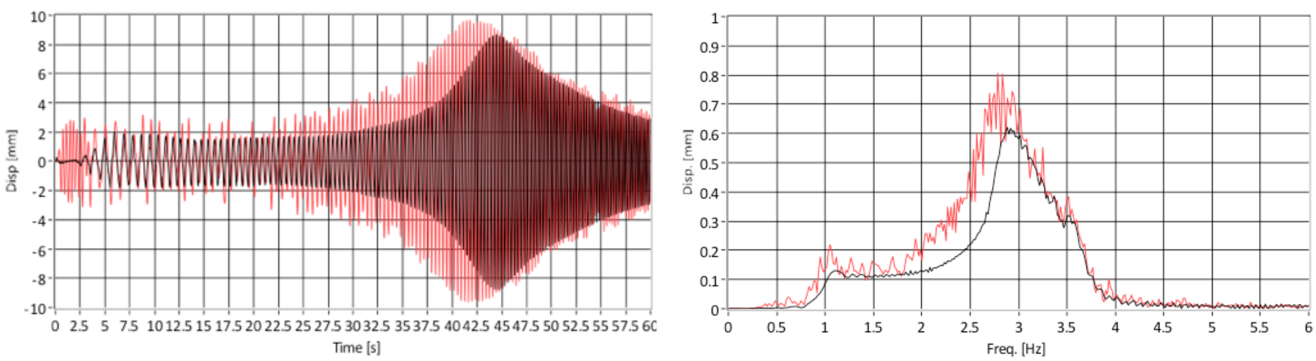
a) Displacement in time domain b) Displacement in frequency domain

Fig. 6 – Relative displacement for El Centro ground motion - (black – shaking table results, red – hybrid simulation results)



a) Displacement in time domain b) Displacement in frequency domain

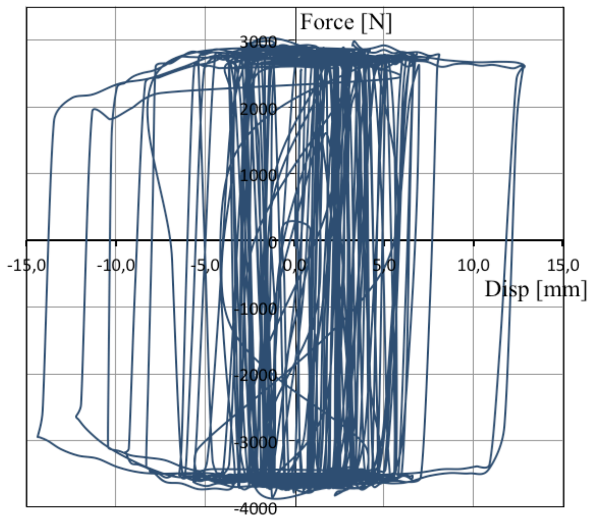
Fig. 7 – Relative displacement for Ulcinj-Albatros ground motion - (black – shaking table results, red – hybrid simulation results)



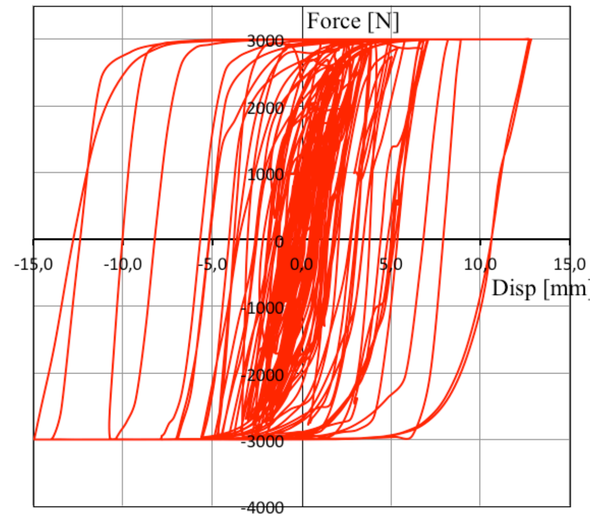
a) Displacement in time domain b) Displacement in frequency domain

Fig. 8 – Relative displacement for Sine-sweep ground motion - (black – shaking table results, red – hybrid simulation results)

Fig.9 shows the hysteresis loops of the numerically simulated and the tested UHYDE-*fbr*. The maximum displacements of the hysteresis loops show good overlap. The numerically simulated device is adjusted to have a yielding force of 3 kN, while the recorded yielding force reaches 3.5 kN but only in one direction. The causes of this one sided overshoot are under investigation.



a) Tested UHYDE-*fbr*



b) Numerically simulated device

Fig. 9 – Hysteresis loops of the tested and numerically simulated UHYDE-*fbr* for the El-Centro ground motion

4. Further research

Results of the initial hybrid simulation tests with constant UHYDE-*fbr* air pressure are very promising. Very good overlap with the results of the shaking table tests was achieved. Further on, displacement, velocity and acceleration dependent levels of air pressure in the UHYDE-*fbr* for different ground motions will be tested. The dependency will be the same as the one used in in IZIIS shaking table tests [17]. If good overlap of the results is achieved, reliability of the test setup can be confirmed.

Research will further concentrate on using hybrid simulation to test the behavior of semi-active devices in large bridges. Numerical simulations of the UHYDE-*fbr* in the ASCE Cape Girardeau benchmark cable-stayed bridge model have already been made and they indicate that great reduction of structural response can be achieved [18]. Authors of the paper used a H2/LQG (linear-quadratic-Gaussian) control algorithm in their research because of its successful application in seismically excited civil engineering structures. This control algorithm was successfully used in many civil engineering applications and is suitable for the stochastic nature of earthquake excitation. That is why the first control strategies that will be tested will be H2/LQG strategies. The authors also used multiple support excitations. Except for very few setups with multiple independent shaking tables, hybrid simulation is the only way to experimentally test the influence of this kind of ground motion.

In later stages of the research other control strategies will be tested on the same bridge. An adaptation of control algorithms will be attempted, first for seismic and then for wind and traffic loads. The goal is to develop integrated semi-active control strategies that can be used for various dynamic loads. Hybrid simulation enables to test these strategies by linking the numerical model with the real semi-active device and also to adjust the constitutive models of the simulated devices through direct comparison with the results of the experimentally tested device. After the control algorithms have been evaluated on the benchmark bridge, other validated numerical models of large bridges can be tested.

The final goal of the research is to investigate the potential of semi-active control in enabling to build more robust, slender and cost-effective large bridge structures. Semi-active control will be utilized in this numerical model for mitigation of vibrations caused by dynamic loads. For that purpose a numerical model of a bridge with a very large span should be developed. Since dynamic loads are the prevalent factors that influence a span of a bridge, an increase in achievable spans is expected.

5. Conclusion

A test setup consisting of a movable steel structure connected to a semi-active device and a hydraulic actuator that can replicate the motion of a single DOF of a structure in hybrid simulation experiments has been built at the University of Kassel. Its primary use is to test semi-active control strategies. Currently used semi-active device is the patented air pressure controlled bi-directional friction device UHYDE-*fbr*.

In order to test the feasibility of this test setup, the results acquired by the use of hybrid simulation have to be compared to the results of real world reference tests. Shaking table tests conducted in IZIIS Skopje within the ISUbridge project are used as reference tests. In that testing campaign two UHYDE-*fbrs* were used to replicate the behavior of different passive device on the connection of the piers and the deck of a scaled model of a deck bridge.

First results of hybrid simulation experiments with constant air pressure in the UHYDE-*fbr* show very good overlap with the results of the shaking table experiments. Same levels of peak amplitudes at the same frequencies were acquired.

Further research will consist of testing different semi-active control strategies for large bridges, especially the ASCE benchmark bridge. One of the first algorithms to be tested will be the H2/LQG algorithm because of its successful implementation in previous studies. Modifications and adjustments of control algorithms for different dynamic loads will be attempted and tested in the developed hybrid simulation environment.

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