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Output-only Finite Element Model Updating for Post-Earthquake Monitoring

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ABSTRACT: After any seismic event, it is critical to rapidly assess the damage condition of bridges. This process could be facilitated using digital technologies to eliminate the barriers of manual inspections. The post-event response of a bridge can be simulated using the bridge's prior finite element (FE) model and recorded ground motions at nearby stations. But, the simulated responses are unreliable due to the uncertainties in the structural and soil properties, as well as input motion at the foundation level. These uncertainties can be reduced through integration of measurement data and the prior FE model using model updating techniques. This study presents a Bayesian model updating technique that jointly updates the FE model of bridge, including the soil-structure effects, and foundation input motions using the measured structural responses. After verification of this technique in a numerically simulated environment, real seismic data are used in a series of case studies. The agreement between the measurements and FE-predicted responses shows the applicability of this technique in a real-world setting. Moreover, comparison between estimated foundation input motions and free-field motions reveals valuable information regarding the soil-structure interaction effects at the bridge site. The updated model is the bridge digital twin and is used for virtual sensing. Using the bridge digital twin, the bridge's local-level responses can be monitored to identify the location/severity of damage.

1. INTRODUCTION

Mechanics-based Finite Element (FE) models are vastly used for seismic response simulation of bridges. However, soil-structure interaction (SSI), dynamic input excitation, damping energy dissipation mechanisms, etc. are of the main sources of uncertainties in these models. The uncertainties in these models can be reduced through a model updating process. In this process the initial FE model is integrated with measured responses of the structure through a data assimilation approach (Ebrahimian et al. (2018)). The updated model is the digital replicate of the bridge and is referred to as its digital twin (DT). The DT is an evolving platform that can be used for response prediction, rapid post-earthquake damage assessment and asset management of bridge infrastructures. The aim of this study is to proceed towards the application of model updating and digital twinning for the purpose of post-earthquake assessment of bridges.

2. METHODOLOGY

In seismic events, while the free-filed motions (FFMs) are recorded by installed sensing devices, the theoretical inputs to the soil-structure interactive system of bridges cannot be explicitly measured (Wolf (2004)). Based on this, development of bridges' DT using seismic measurements requires estimation of the foundation input motions (FIMs). In this study, an output-only sequential Bayesian inference using the unscented transformation approach is used to jointly update the bridge FE model and estimate the FIMs. In this approach, the unknown FE model parameters and FIMs are treated as random variables. The uncertainties of these variables are characterized by a joint probability density function. The prior uncertainties in the unknown parameters, characterized by corresponding mean vectors and covariance matrices, are propagated through the FE model of the bridge and stochastic FE-predicted responses are estimated. Using the Bayes' theorem, the posterior estimates of mean vector and covariance matrix of unknown variables are determined. The details of this approach can be find in Ghahari et al. (2022).

Performance of model updating process relies on correct selection of updating model parameters. The model parameters with the highest sensitivity to the available measurements are required to be selected as the updating parameters. In this study, the updating parameters are selected using the identifiability analysis approach presented in Ebrahimian et al. (2019). In this approach, the information gain of each model parameter from each measurement channel is calculated as the difference between the *a priori* and *a posteriori* information entropy. Moreover, to calculate the sensitivities of measurements with respect to model parameters a finite difference method is employed.

In this paper, the performance of the model updating process is first verified using the FE model of San Roque Canyon (SRC) bridge which is a reinforced concrete box girder highway bridge in Santa Barbara, California. Then, the seismic data collected from the SRC bridge station are used for real-world case studies. Afterwards, the digital twin of the SRC bridge is utilized for the purpose of virtual sensing.

3. CASE STUDY USING NUMERICAL DATA

To evaluate the performance of the model updating algorithm, a precast reinforced concrete bridge (SRC) is used as a testbed. The geometry of the bridge and its instrumentation layout are shown in Figure 1. The FE model of the bridge is developed in OpenSees (McKenna (2011)) based on the guidelines available in Aviram et al. (2008). All the nominal material properties are taken from the as-built structural drawings and Caltrans Seismic Design Criteria (Caltrans (2013)). The details of the FE model are shown schematically in Figure 2. More details can be find in (Ghahari et al. (2022)).

The list of earthquakes recorded in the bridge station is presented in Table 1. Identifiability analysis is carried out using 2004 Isla Vista earthquake as the input ground motion. Identifiability of 34 model parameters are studied and for the sake of brevity, only the final results are presented here. The studied parameters include concrete modulus of elasticity, concrete compressive strength, bearing pads' stiffness, soil-foundation stiffness and damping under piers and abutments, abutments' embankment mass, far-field soil-embankment stiffness and damping, soil-backwall stiffness and Rayleigh damping coefficients. The results show that parameters presented in Table 2 have the most identifiability and are selected to be updated using model updating process.

Table 1: Recorded earthquakes.

Event name	Date	Distance	PGA
San Simeon	12/22/2003	187.0 (km)	1.5%g
IslaVista	05/09/2004	27.2 (km)	1.6%g
IslaVista	05/29/2013	18.0 (km)	4.1%g
Montecito	04/23/2017	9.5 (km)	2.2%g
Sata Cruz	04/05/2018	67.9 (km)	2.6%g

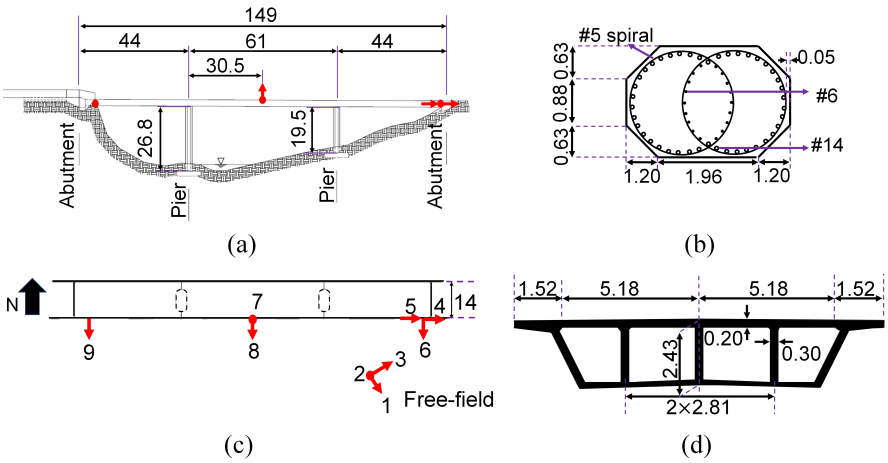

Figure 1: The SRC bridge geometry and its instrumentation layout: (a) elevation view, (b) pier section, (c) plan and accelerometers layout, and (d) deck section. All the dimensions are in meters.

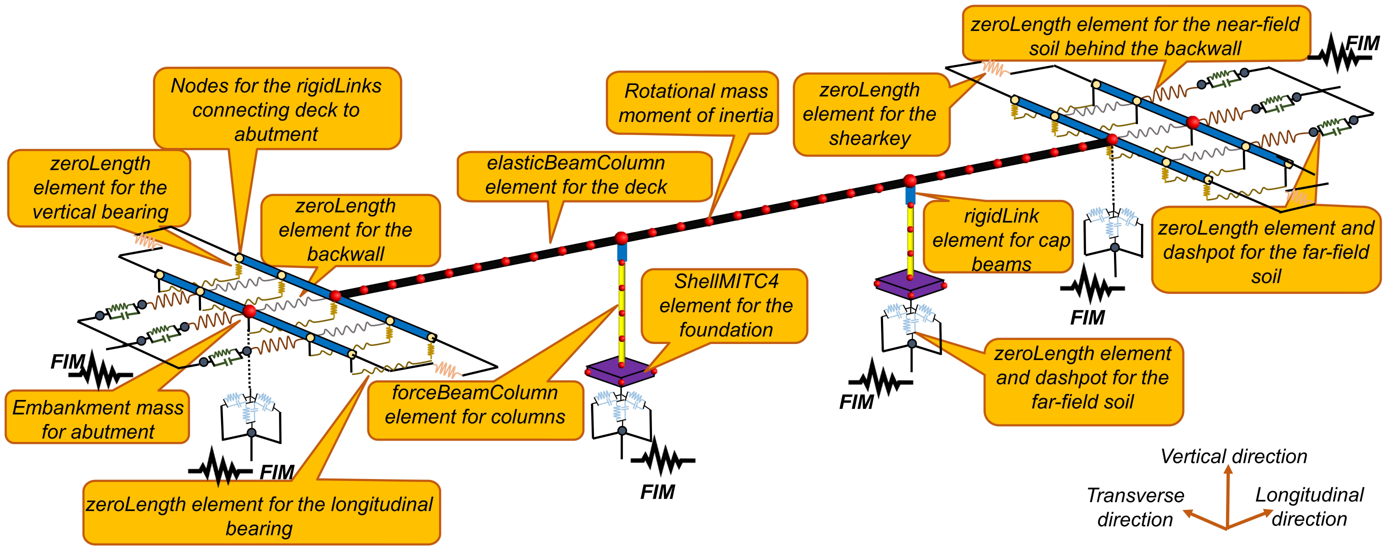

Figure 2: Schematic view of the bridge's FE model.

Table 2: Identifiable unknown model parameters and their nominal values.

parameter	Description	Nominal value
E_d	Deck's modulus of elasticity	27.8 GPa
E_c	Columns' initial modulus of elasticity	27.8 GPa
k_T^b	Bearing pads' transverse elastomeric shear stiffness	100 MN/m
k_L^b	Bearing pads' longitudinal elastomeric shear stiffness	10 MN/m
a_0	Mass proportional Rayleigh damping coefficient	0.6 sec^{-1}
a_1	Stiffness proportional Rayleigh damping coefficient	0.003 sec

To verify the model updating algorithm in a numerically simulated environment, the measurements are simulated using the FE responses of the bridge to the 2004 Isla Vista earthquake (free-field motions are used as FIMs). The FE responses are polluted with a zero-mean Gaussian noise with 5%

root mean square noise-to-signal ratio and are used as simulated measurements. These measurements are used in the model updating process to estimate the unknown model parameters as well as the FIMs. The initial values for the unknown model parameters are set equal to 80% of their nominal values that are listed in Table 2. For the sake of presentation, only agreement between measurements and estimated responses in channel 5, and agreement between true and estimated FIMs in the longitudinal direction are shown in Figure 3. Further results can be find in Ghahari et al. (2022). The estimation error in the updating process of model parameters are shown in Figure 4. These figures show that the model updating algorithm is successful in estimation of measurements and FIMs while the unknown model parameters are gradually updated to their corresponding true values.

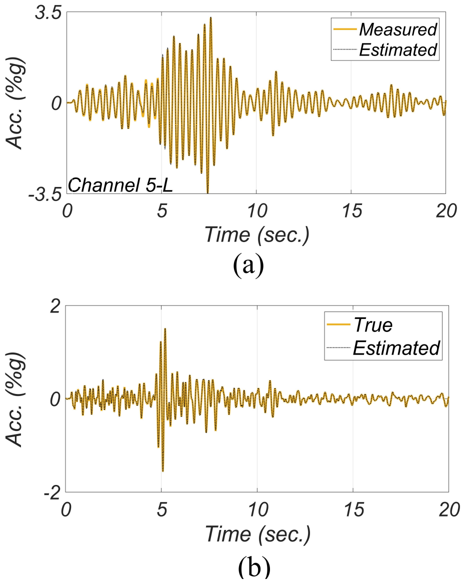

Figure 3: Comparison between the true and FE-predicted (a) accelerations in channel 5, and (b) FIMs in longitudinal directions.

4. CASE STUDY USING REAL-WORLD DATA

In this section, the model updating process is carried out using the real-world acceleration data collected during the earthquakes listed in Table 1. The initial values for the unknown model parameters are set to the nominal values presented in Table 2. The normalized final estimates of model parameters and their event-to-event variability are shown in Figure 5. In this figure, parameter E_{ave} shows the average of updated values for parameters E_d and E_c. A minor variation is observed in the final estimate of parameter E_{ave} in different events. This variation is most probably due to concrete aging and modeling error. The final estimates of parameter k_T^b are higher than parameter k_L^b in all events. This can be understood from Table 2 and Figure 5. This observation was expected as parameter k_L^b only reflects the elastomeric pad effects, while the parameter k_T^b accounts for the simultaneous contribution of the elastomeric pad and shear key. The final estimates of parameters k_T^b and k_L^b are higher for the 2018 Santa Cruz earthquake than the other events. This is justifiable as 2018 Santa Cruz earthquake is the weakest studied event with the smallest PGA value (see Table 1). Since bearing pads are stiff enough to prevent any movements in such a weak event, the measurements are not sensitive to the parameters k_T^b and k_L^b. This condition can results in large estimations for these parameters.

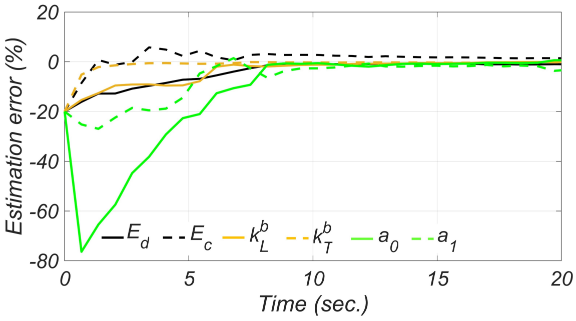

Figure 4: Updating process for model parameters.

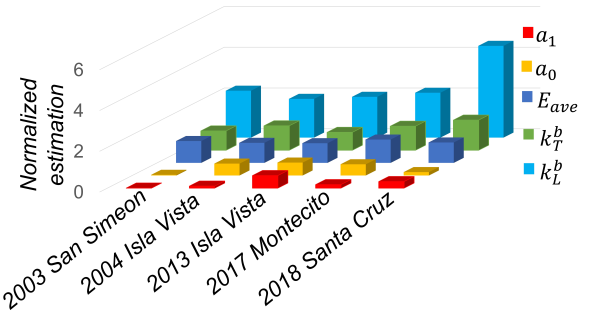

Figure 5: Final estimates of unknown model parameters in different events. These values are normalized to the corresponding initial/nominal values.

Using the final estimates for damping coefficients, Rayleigh damping is calculated and presented in Figure 6. Based on this figure, the least and the highest damping is experienced in 2003 San Simeon and 2013 Isla Vista events, respectively. The reason for small damping estimation in 2003 San Simeon event is coming from the dominance of low-frequency contents in the pseudo spectral acceleration of FFMs in this event (Ghahari et al. (2022)). Superiority of low-frequency content results in quasi-statically response behavior of the bridge and small damping in 2003 San Simeon earthquake. On the other hand, 2013 Isla Vista event has the highest intensity among the studied earthquakes, and the highest estimation of damping for this event reveals a dependency between inherent damping and the intensity of the event.

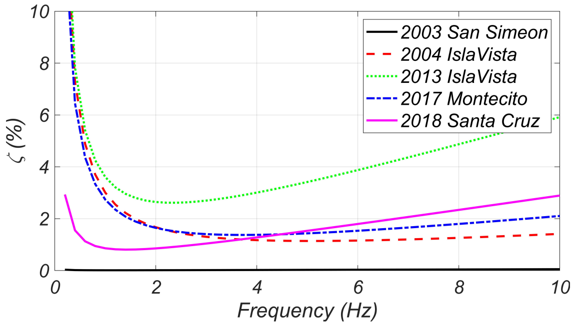

Figure 6: The final estimates of the Rayleigh damping ratio.

Comparisons between the final estimates of FIMs with the measured FFMs are shown in Figure 7 and Figure 8. It is noteworthy that discrepancies between FFMs and FIMs, quantified using relative root mean square error (RRMSE) (Ghahari et al. (2022)), represent the SSI effect and the higher the RRMSE, the greater the SSI effect. It should be noted that channel 3 malfunctioned during the 2017 Montecito and 2018 Santa Cruz earthquakes. Hence, measurements at channels 4 and 1 are reported as the measured FFMs in the longitudinal and transverse directions for these two events. As can be seen in Figure 7, there is a good fit between FE-predicted FIMs of 2017 Montecito and 2018 Santa Cruz events and measurements of channel 4 which is installed on the abutment. This observation shows that there is likely no significant bridge-abutment interaction. The best match between FFMs and FIMs is observed in 2003 San Simeon event which reveals small SSI effects due to the low-frequency content of this event. In general, there are better agreements between the FIMs and FFMs in the longitudinal direction than the transverse direction. This difference suggests minor kinematic and inertial interaction for this bridge under the studied motions in the longitudinal direction.

For the sake of presentation, comparisons between the final estimates and measured accelerations are only shown for 2003 San Simeon. Further results are available in Ghahari et al. (2022). In overall, Figure 9 shows that the updated model predicts the measured accelerations successfully.

5. DIGITAL TWINNING AND VIRTUAL SENSING

The updated FE model of the bridge is a presentation of the bridge in digital world and is known as the bidge's digital twin (DT). In this section, the DT developed using 2013 IslaVista earthquake is employed to screen the local element- and material-level responses of the bridge for the given input motion. The results can be used to assess damage at the local levels of the bridge. This procedure is referred to as virtual sensing (Ghahari et al. (2022)). Figure 10 shows an example for monitored local level response which is the stress-strain response of the extreme concrete fiber at the lowest section of the west pier. As can be seen, the bridge behaves in its linear-elastic regime. This is because that the recorded events at the site of SRC bridge are relatively weak (see Table 1) and no damage is anticipated. However, similar idea is relevant for the strong motions.

Another application for DT is near real-time damage assessment of the bridge in case of new seismic events. For this purpose, the local level response of the bridge is evaluated in a series of forward simulations when the bridge is subjected to ground motions with different intensities. The results provides a primary near real-time evaluation of the bridge condition once the intensity of the new event is known. Afterwards, model updating process can be carried out to indicate more de-

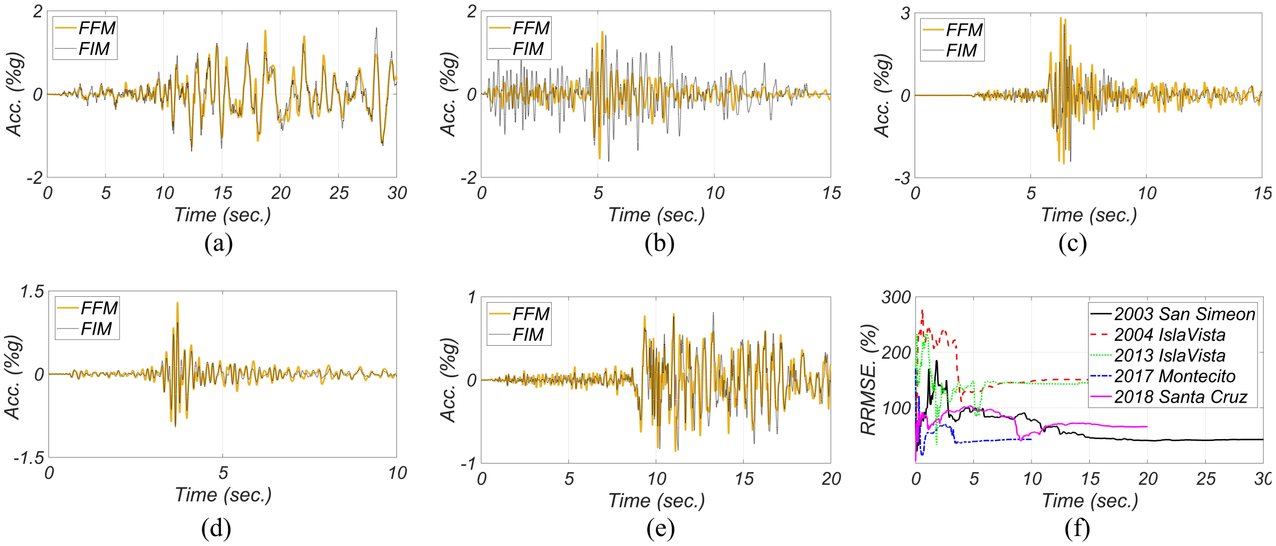

Figure 7: Comparing the recorded FFMs and FE-predicted FIMs in the longitudinal direction for (a) 2003 San Simeon, (b) 2004 IslaVista, (c) 2013 IslaVista, (d) 2017 Montecito, and (e) 2018 Santa Cruz, earthquake events. Part (f) is the RRMSE between the FE-predicted FIMs and recorded FFMs.

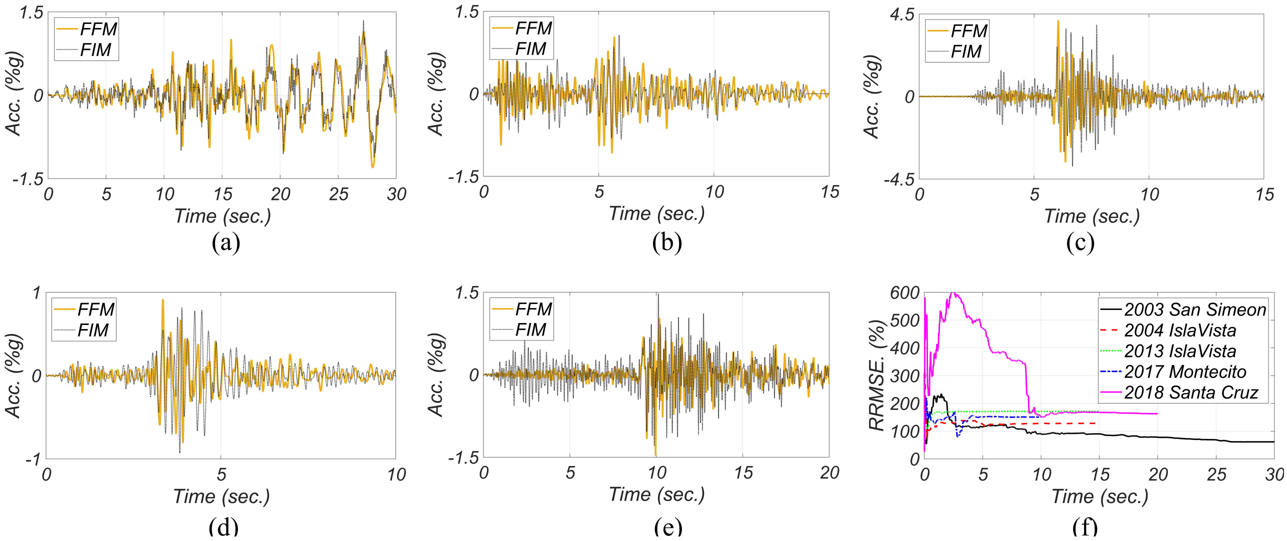

Figure 8: Comparing the recorded FFMs and FE-predicted FIMs in the transverse direction for (a) 2003 San Simeon, (b) 2004 IslaVista, (c) 2013 IslaVista, (d) 2017 Montecito, and (e) 2018 Santa Cruz, earthquake events. Part (f) is the RRMSE between the FE-predicted FIMs and recorded FFMs.

tailed/accurate post-event damage assessments and also update the DT for future events.

6. CONCLUSIONS

This study presented the procedure for bridge digital twinning and virtual sensing through an output-only Bayesian time-domain model updating technique using seismic data. The performance of this method was first verified in a numerically simulated environment. A detailed finite element model of the studied bridge was developed in OpenSees. Then, the unknown model parameters with the most identifiability were selected through an identifiability analysis. The verification study presented good performance of the model updating process in joint estimation of the unknown model parameters and the time history of foundation input motions (FIMs). In the next step, the application of

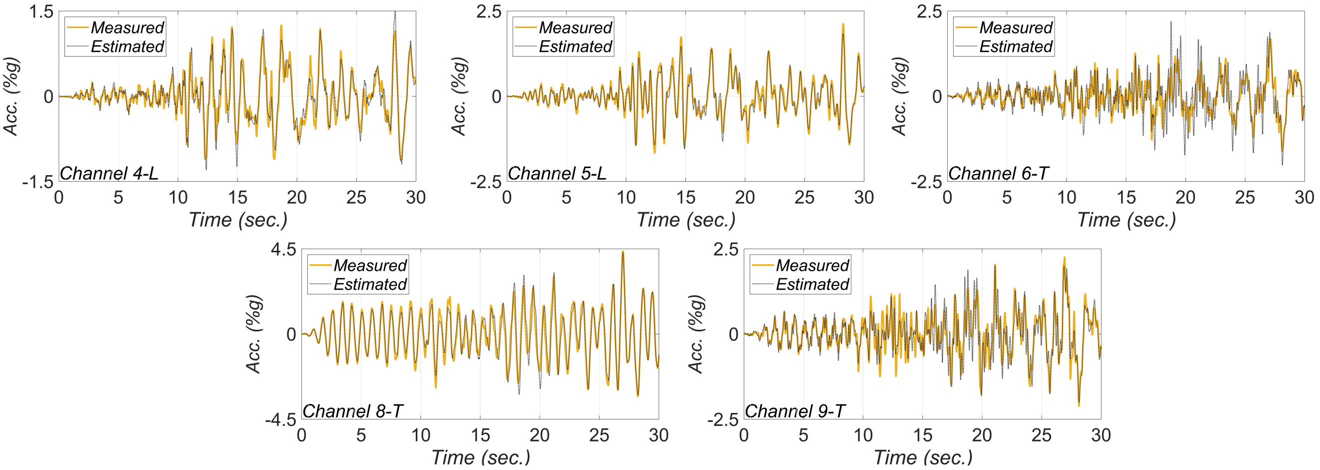

Figure 9: Comparing the measurements and FE-predicted accelerations for 2003 San Simeon earthquake.

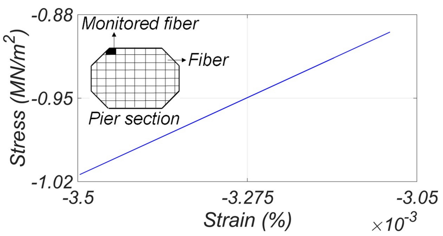

Figure 10: Monitored stress-strain response in the extreme fiber at the lowest section of the west pier using the bridge's DT.

the model updating technique was examined for damage identification and bridge digital twinning through real-world case studies. The findings confirm the following conclusions:

- Discrepancies between measured free-field motions (FFMs) and estimated FIMs reveal information regarding the soil-structure interaction effects at the bridge site.
- There is a correlation between the inherent damping of the bridge and the intensity of the ground motion.
- The final estimates of bearing pads' stiffness have the largest event-to-event variations compared to the other model parameters. This is due to the dependency of bearing pads' stiffness to the intensity and frequency content of the input ground motion.
- Digital twins can be used for near real-time post-event damage assessment and virtual sensing.

To better understand the limitations and capabilities of the Bayesian model updating process for structural health monitoring and damage diagnosis, additional studies of this type with different structural systems and loading conditions (e.g., traffic, wind, etc.) are required.

7. REFERENCES

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