# SEISMIC SIMULATION OF OVERHEAD CRANE ON SHAKING TABLE: OVERVIEW AND LESSONS LEARNED

**Benjamin Richard[1], David Bouhjiti[2], Charles Droszcz[3], Emmanuel Viallet[4]**

[1] Head of Mechanical Equipment Safety Review Office, French Authority for Nuclear Safety and Radiation Protection, ASNR/PSN-EXP/SES/B2EM, Fontenay-aux-Roses, France (Benjamin.Richard@asnr.fr)
[2] Head of the Structural Performance Analysis and Modelling Lab, French Authority for Nuclear Safety and Radiation Protection, ASNR/PSN-EXP/SES/LMAPS, Fontenay-aux-Roses, France (David.Bouhjiti@asnr.fr)
[3] Engineer, Geodynamique & Structure, France (charles.droszcz@geodynamique.com)
[4] Seismic Hazard Expert Fellow, Électricité de France, Engineering and Supply Chain Division, Technical Direction, Lyon, France (Emmanuel.Viallet@edf.fr)

## ABSTRACT

This paper deals with the issue of the dynamic response of overhead crane bridges under seismic loads within nuclear power plants. It presents a summary of results and shares the feedback following SOCRAT (Seismic simulation of Overhead CRAne on shaking Table) international benchmark carried out from June 2020 to February 2022 jointly by the French TSO Institute for Radiological Protection and Nuclear Safety and the French operator Electricité de France under the umbrella of the OECD/NEA. The benchmark was primarily aimed at comparing numerical modelling strategies given an increasing seismic load applied to a 1:5 scale mock-up of a typical overhead crane. Narrow-band seismic signals were selected based on the July 2007 Chüetsu-oki main shock earthquake recordings at a height of 22 meters in the turbine building of unit 5 of Kashiwazaki-Kariwa nuclear power plant. The experimental tests were carried out in 2015 on the AZALEE shaking table operated by the French Sustainable Energy and Atomic Energy Commission in Saclay (France). On the one hand, their results show that the global dynamic response of overhead cranes can be captured with a large variety of modelling approaches, from the most simplified to the most complex ones, if the most influential physical phenomena are accurately accounted for (local shocks, sliding, friction, etc.). On the other hand, provided results show that the local response modelling is not easy to achieve with a high confidence level given the strong nonlinearities and the inherent localized uncertainties (surface state, initial position of each component, asymmetry of the assembly, etc.). To provide practitioners with the range of uncertainties one could expect and the gaps to the real behaviour for this kind of modelling, the scatter of Engineering Demand Parameters of interest (maximum accelerations, support reactions, displacements) is provided and assessed. Based on the benchmark results, such scattering is important but can be reduced given a number of consensual recommendations which are listed at the end of the paper.

## INTRODUCTION

Crane bridges are widely used in the nuclear industry to handle, lift, and transfer heavy loads. They can be found in various buildings belonging to the nuclear island of nuclear power plants (NPPs). Assessing their dynamic behaviour is recognized to be an important issue for nuclear safety. Indeed, despite a favourable seismic behaviour (EPRI, 2005), within the context of seismic Level 1 Probabilistic Safety Assessment (PSA) studies, these devices have been identified as significant contributors in the probability of core meltdown when their failure occurs. Depending on the reactor design and on the age of the reactor, one of the significant failure modes can be related to anchorage failure during earthquake. Therefore, the issue of dynamic behaviour of crane bridges needs to be considered within the global framework of the safety demonstration of a plant and, especially, to properly estimate the forces transmitted to the anchors.

There are only few studies on the seismic behaviour of overhead crane bridges. (Komori et al., 1989) conducted tests on a 1/10 scale model to study the sliding of the wheels on the rails under horizontal seismic excitation, and (Otani et al., 2002) performed seismic tests on a 1/8 scale model to study the vertical behaviour, including the rebound and impacts of the crane bridge on the rolling structure. These studies showed that linear analysis can be used to estimate the reaction forces at the wheels level. However, a considerable margin (30% according to (Otani et al., 2002)) is found to be necessary to evaluate the wheel reaction forces in the overhead crane design if any leap of the crane is expected.

In (Schukin et al., 2007), the authors used a finite element model to study the seismic behaviour of a polar crane bridge. Sensitivity studies showed that the friction between the wheels and the rail has a significant influence on the seismic response of the crane. Properly considering this friction can reduce the seismic response by 4 to 6 times. (Betbeder-Matibet et al., 1992) discussed simplified approaches that account for the reduction in crane bridge forces due to sliding, such as using a reduced spectral response to take sliding into account.

In 2010, IRSN and the French Sustainable Energy and Atomic Energy Commission (CEA) carried out an experimental campaign on a 1/5 scale mock-up of a crane bridge under seismic loads using the AZALEE shaking table at CEA (Feau et al., 2015). The tests were conducted for different configurations (trolley location, braked and rolling wheels) under various excitation signals (bi-axial, tri-axial, growing PGA values). The first objective was to study the ability to numerically reproduce the highly non-linear behaviour of crane bridges. Then, a second experimental campaign was conducted in 2015 with the same mock-up with an additional focus on the forces transferred between the mock-up and the table upper plate (this was not measured during the 2010 campaign). The large experimental database generated through this campaign were used to perform a series of numerical simulations as parts of the benchmark. On the one hand, some of these data were used by the participants to characterize and calibrate their models and, on the other hand, other data were used to assess the predictive capacity of the used modelling strategies.

SOCRAT benchmark consisted of two major stages, namely Stage #1 and Stage #2 each of which lasted approximately 6 to 7 months:

(i) Stage #1 is focused on the development and on the characterization of the numerical models. General information on the numerical models developed by the participants as well as specific information on how the models describe local contacts and shocks was collected. At the end of Stage #1, an online workshop was organized to sum up the results obtained by the participants before moving on to the second stage #2;

(ii) Stage #2 aims at allowing the participants to perform five blind predictive exercises based on the previous calibrations achieved during stage #1. this was done for the whole crane bridge model under high intensity seismic loads and strong nonlinearities (shocks, sliding, friction).

This paper aims at giving an overview of the work performed within the framework of the SOCRAT benchmark. The paper is outlined as followed. In section 2, the benchmark organization is described as well as the experimental database. In sections 3 and 4, some results are shown before exposing in the conclusive part the output recommendations.

## BENCHMARK ORGANIZATION

### *Description of the mock-up*

The mock-up is a simplified 1/5 scaled model of a 22.5 m long overhead crane. Its dimensions have been derived from the dimensions of the crane used in the PHENIX research reactor. Given that the AZALEE shaking table measures 6 m x 6 m, this scale is the biggest one can consider. The crane mock-up is composed of the following components (see **Erreur ! Source du renvoi introuvable.**): a trolley, rails and wheels, two girder beams, two end truck beams, two runway beams, and four load cell blocks which are included in the supports between the shaking table upper plate and the crane bridge mock-up. Each load cell block is composed of 4 load cells.

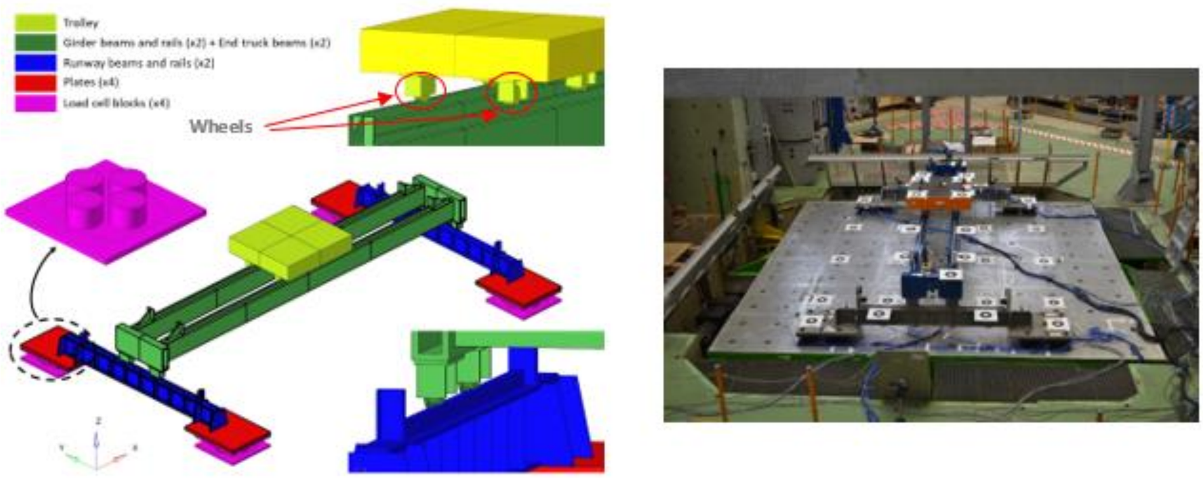


Figure 1: The left side shows the components of the model while the right side shows the top view of the mock-up on the AZALEE table (Mongabure et al., 2017).

One important issue for the design of the mock-up was the determination of the similitude law and the details of this choice are presented in (Feau et al., 2015).

### *Benchmark agenda*

The SOCRAT International Benchmark consisted of two major stages, namely Stage #1 and Stage #2, and two scientific workshops. The participants' results remained anonymous. Figure 2 gives an overview of the benchmark schedule.

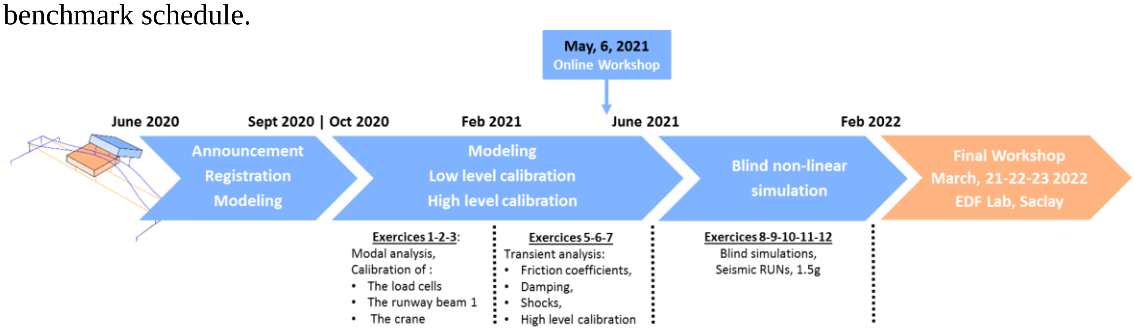


Figure 2 : SOCRAT international benchmark agenda.

After the kick-off and the registration of participants between June and September 2020, the first modelling and model calibration Stage was held until June 2021 and ended with an online workshop. This workshop brought together participants, as well as steering and expert committees. The steering committee gave a general presentation to remind participants about the context, objectives, and agenda of the benchmark, and to review the exchanges that took place during the first stage. Participants then had the opportunity to present their work and highlight the challenges they faced. Stage 2 of blind calculations then took place until February 2022, then the international benchmark closing workshop in Paris in March 2022.

### *Benchmark participants*

The SOCRAT Benchmark received 22 applications. In the following, an overview of the 19 participants who sent results for at least one exercise is presented. There are mainly participants from European countries and two from Asia. There are about 7 participating countries spread over different areas, from academia to the industry, including the nuclear industry: some represent nuclear power plant operators or energy producers, others and most participants are consulting companies, we also have nuclear regulatory authorities, technical support organizations and one software company.

- AERB - Atomic Energy Regulatory Board - Team 1 (India)
- AERB - Atomic Energy Regulatory Board - Team 2 (India)
- ATR (France)
- CETIM Senlis (France)
- CKTI - Vibroseism Ltd. (Russia)
- CNAM - Conservatoire National des Arts et Métiers (France)
- EGIS INDUSTRIES (France)
- ENSI Team B&H - Basler & Hofmann AG (Switzerland)
- ENSI Team Principia/SPI (Spain)
- ENSI Team SPI - Stangenberg & Partners Consulting Engineers (Germany)
- ESI (France)
- ESTP - Ecole Spéciale des Travaux Publics (France)
- F4E – ESTEYCO (Spain)
- GRS - Gesellschaft für Anlagen und Reaktorsicherheit (Germany)
- INSA Lyon / Laboratoire GEOMAS (France)
- Nuclear Power Corporation of India Ltd. (India)
- OKG Aktiebolag (Sweden)
- ORANO (France)
- TECHNIA (Sweden)

## OVERVIEW OF STAGE #1: MODELLING ASSUMPTIONS AND INITIAL STRUCTURAL CALIBRATION

### *Main content*

Stage #1 is focused on the development, the characterization of the numerical models and on modal calibration. The efficiency of a finite element model, in the case of a linear elastic calculation, depends mainly on three factors:

1. the definition of a mesh to ensure it is geometrically representative of the mock-up;
2. the definition of the interfaces between the different components of the mock-up;
3. the definition of the boundary conditions.

The calibration process of the model can be performed at different levels. This stage includes component-level calibration and mock-up-level calibration.
Table 1 presents an overview of the exercises requested in Stage #1.

Table 1 : Overview of the exercises requested in stage #1.

| Exercise | RUN(s) | Configuration | Input signal | Component | Description |
|---|---|---|---|---|---|
| 1 | 1, 4, 8 | - | Hammer shock | Load Cell Block | Modal Calibration |
| 2 | 17, 18, 19 | - | White noise signal | Runway beam | Modal Calibration |

| | | | | | |
|---|---|---|---|---|---|
| 3 | 33 | Blocked state | White noise signal | Crane mock-up | Modal Calibration |
| 5 | 64 | Fixed centred | X signal excitation | Crane mock-up | Sliding characterization |
| | 62 | Sliding centred | Y signal excitation | Crane mock-up | Sliding characterization |
| | 82 | Mixed centred | Y signal excitation | Crane mock-up | Sliding characterization |
| 6 | 117 | Decentred sliding | Seismic - Tri-axial (1.0g) | Crane mock-up | Vertical displacement |
| 7 | 53 | Centred sliding | Seismic - Tri-axial (0.5g) | Crane mock-up | Seismic response |

***Natural frequencies***

In exercise 2, participants were invited to carry out modal analyses on a single runway beam (in blue in **Erreur ! Source du renvoi introuvable.**), including its two load cell blocks, and of the complete crane, including its four load cell blocks. In the following, only the results obtained in case of the full crane bridge are presented. The first eigenmode identified experimentally is of bending along the X direction and has a value of 7.57 Hz. The second eigenmode is bending along the Y direction and has a value of 8.31 Hz. The third eigenmode is identified as bending along the Z direction, with a value of 13.27 Hz. Finally, the fourth eigenmode is identified as being a trolley torsion type mode around the X direction, with a value of 16.37 Hz. Thus, the shapes of these modes are illustrated in Figure 3.

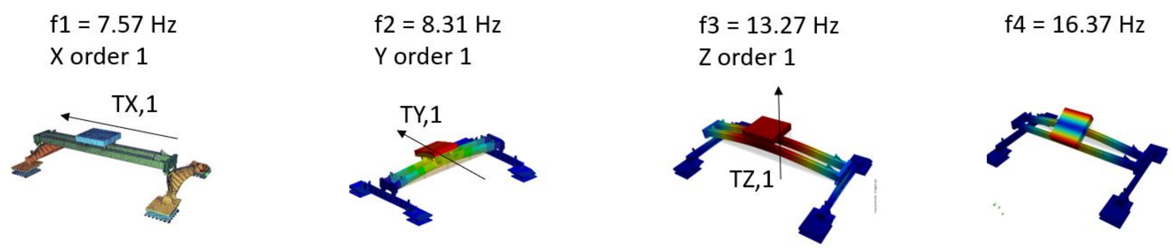


Figure 3: Experimental mode-shapes of the crane.

The results of the modal analysis of the complete crane bridge are summarized in the subsequent box plot in Figure 4. Participants' results are overall satisfactory, with a standard deviation of around 1 Hz for the first three modes, which are the main modes in the X, Y, and Z directions. The standard deviation for mode 4 is 2.5 Hz. We can observe in Figure 9 that the scattering is quite variable depending on the mode we are looking at. The teams that obtained good results which match well the test outputs are the ones that succeeded to obtained satisfactory results also for previous exercises (#1 and #2). More precisely, these teams considered the exact stiffness of the load cells provided by the organizing team and they could manage to do it because they used appropriate/detailed modelling strategy. For other teams, some parameters have been adjusted. Two main parameters are concerned, especially the stiffness of the supporting plates combined with the stiffness of the load cells. Indeed, depending on the modeling assumption and on the type of mesh used, only a simplified stiffness at the supports can be inputted. Their values depend on the model chosen by the teams and therefore, cannot be generalized. This observation means that, in case of the specific mock-up studied in the benchmark, a specific attention had to be paid to the way of modelling the supporting conditions with the shaking table and more generally the boundary conditions.

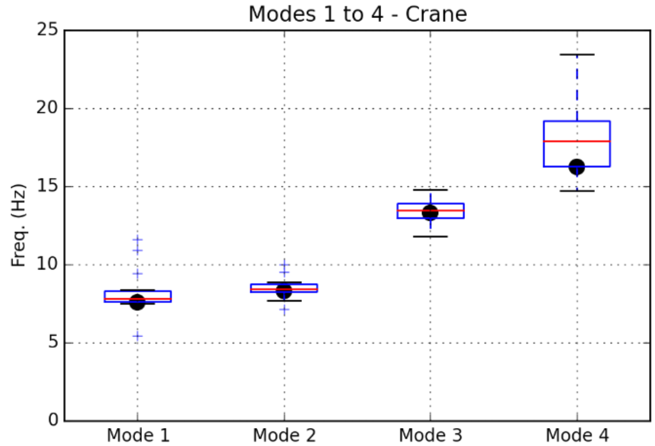


Figure 4: Boxplots of the frequency values provided by the participants for the crane. The black dot represents the experimental value, while the red line indicates the median value of the participants' results. The blue box encompasses the first ($Q_1$) and the third ($Q_3$) quartiles or the 25th and 75th percentiles. The black lines indicate the range between the minimal and maximal value provided by participants

## OVERVIEW OF STAGE #2: MODELLING ASSUMPTIONS AND INITIAL STRUCTURAL CALIBRATION

### *Main content*

Stage #2 of the benchmark, followed the calibration of the models selected by the participants, included blind exercises. This stage aimed to assess the nonlinear response of the crane bridge mock-up under high intensity seismic loadings. The participants were not provided with the experimental results from the RUNs but were given only the seismic signals at the table level as input data for their simulations. The five exercises proposed in this stage are summarized in Table 2.

Table 2: Exercises of Stage #2 – blind simulations.

| Exercise | RUN | Direction | Input - PGA [g] | Crane config. | Wheels config. |
|---|---|---|---|---|---|
| 8 | 80 | XY | 1.5 | Centered | Mixed |
| 9 | 42 | XY | 1.5 | Centered | Sliding |
| 10 | 112 | XY | 1.5 | Decentered | Sliding |
| 11 | 128 | XY | 1.5 | Decentered | Mixed |
| 12 | 100 | XYZ | 1.0 | Centered | Mixed |

The previous runs are multipliers of run 53 which is shown in Figure 10. So only the acceleration amplitude is increased by a factor 2 to 3.

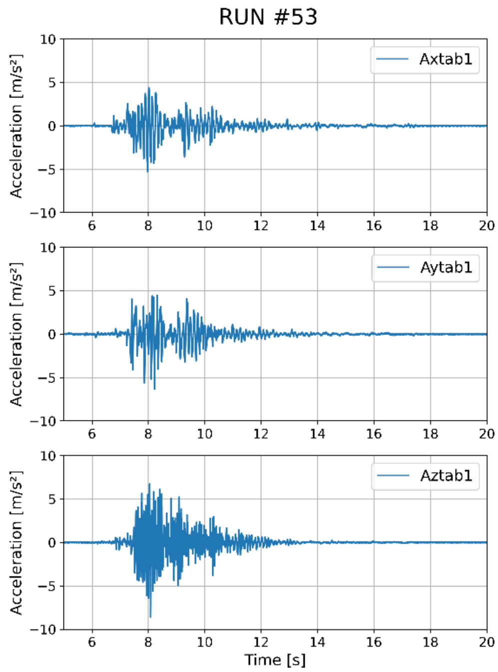


Figure 5: Seismic input signal for run 53 with the following intensity measures: PGA = 0.5g, $U_{T90}$= 2.7s (strong part).

The outputs of Stage #2 simulations performed by the participants are presented in the form of post-processed EDP, including displacements, accelerations, and support reactions. The time evolutions of these parameters were obtained at various points located on the different components of the crane bridge, including the trolley, girder beam, runway beam, end-truck beams, and load cell blocks, as specified in the instructions. The following sections present the results obtained and their analyses.

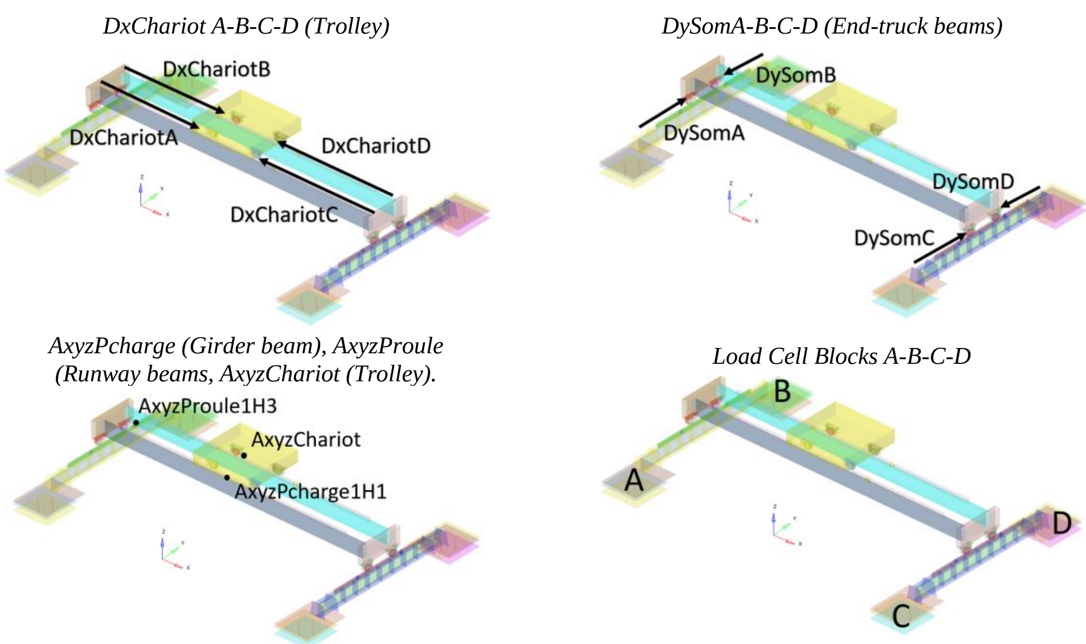


Figure 11: Location of the sensors and the 4 load cell blocks

For each exercise of Stage #2, the participants calculated the accelerations at the trolley (AxyzChariot), girder beam (AxyzPcharge1H1), and runway beam (AxyzProule1H3) in all three directions. The response spectra of these accelerograms were calculated using 2% damping and compared to the one from the test campaign. Similarly to RUN 53, Figure  and Figure  depict the median pseudo-acceleration across all participant values for each frequency in comparison with experimental results.

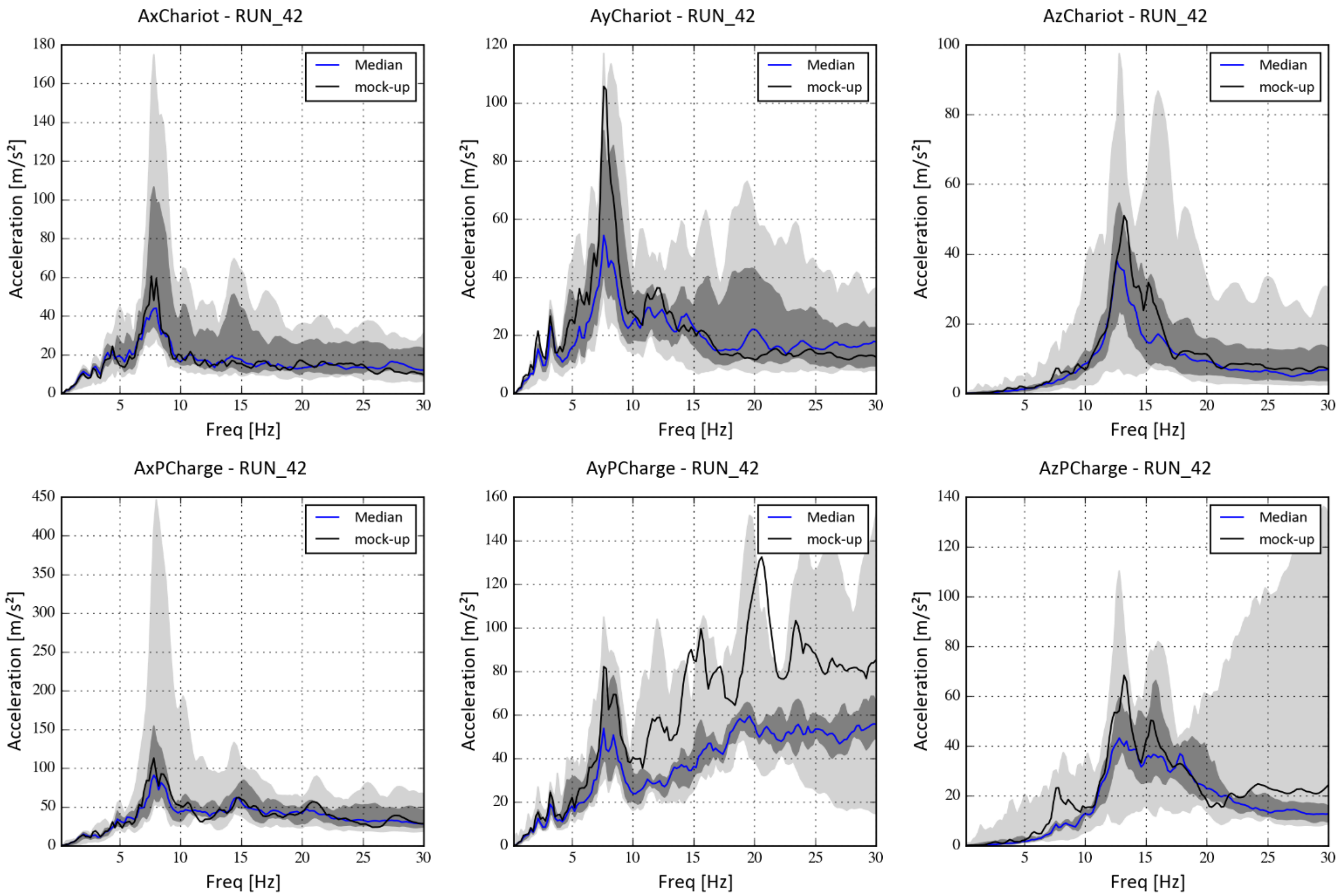


Figure 12: Response spectra (2%) of accelerations at the Trolley and the Girder beam for RUN 42. Experimental results are shown in dark and continuous lines. The median spectrum is depicted in blue and represents the median pseudo-acceleration value for each frequency across all participants. The 1st and 3rd quartile values (25th and 75th percentiles) are represented by the lower and upper spectra and the region between them is shaded in dark grey. The minimum and maximum spectra among participants' spectra and the area between these spectra are shaped coloured in light grey

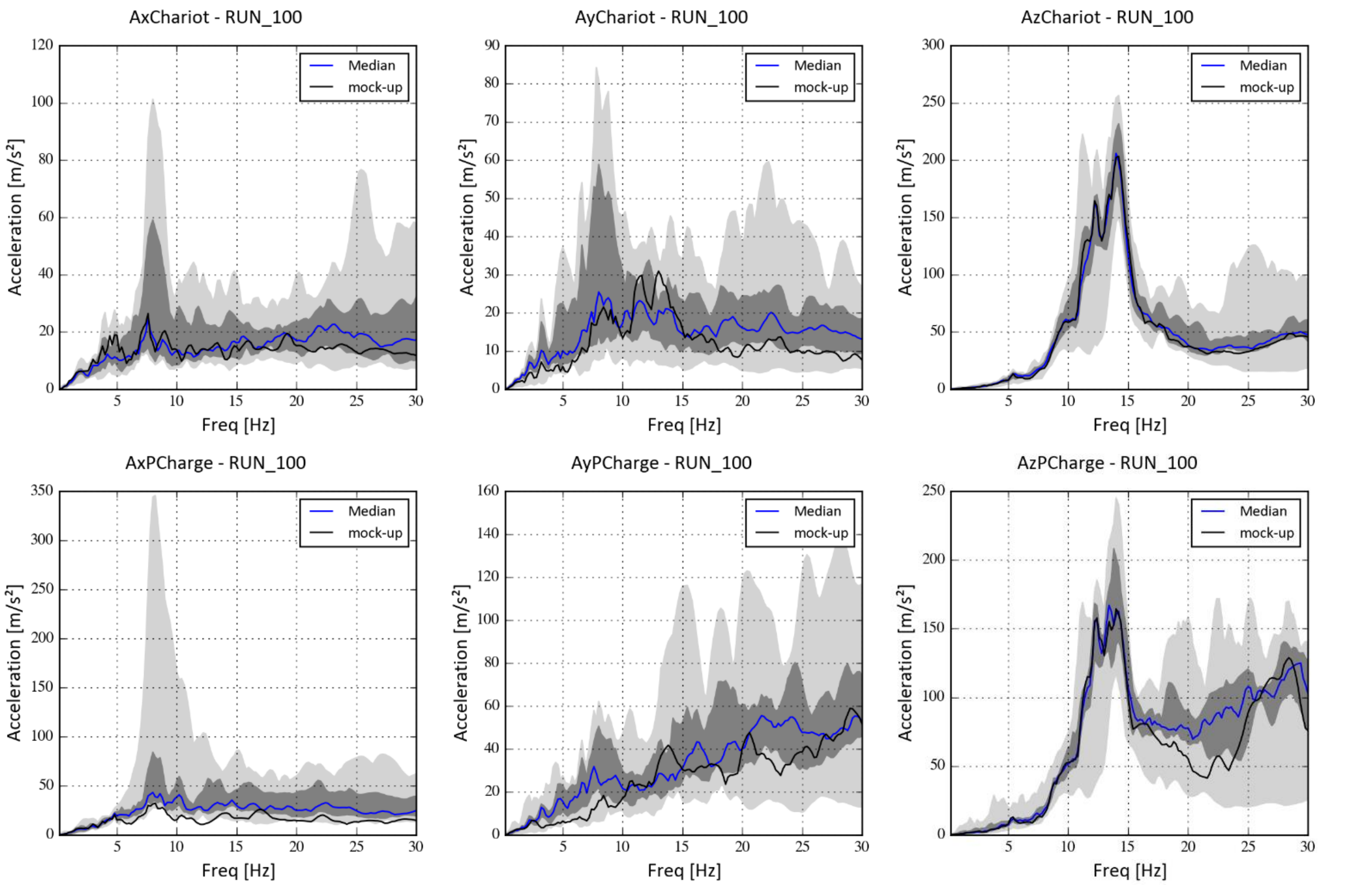


Figure 13: Response spectra (2%) of accelerations at the Trolley and the Girder beam for RUN 100. Experimental results are shown in dark and continuous lines. The median spectrum is depicted in blue and represents the median pseudo-acceleration value for each frequency across all participants. The 1st and 3rd quartile values (25th and 75th percentiles) are represented by the lower and upper spectra and the region between them is shaded in dark grey. The minimum and maximum spectra among participants' spectra and the area between these spectra are shaped coloured in light grey

The spectra calculated for the trolley exhibit a primary peak at 7 Hz for the horizontal direction and 13 Hz for the vertical direction, which aligns with the mock-up and the first modes of the crane. The spectral acceleration calculated by the participants for the trolley is largely consistent with the mock-up spectra, with the results well within the inter-quartile range $Q_1$ - $Q_3$. The vertical direction results are even more accurate for RUN 100 (three-dimensional excitation), where the median spectrum of the participant values matches the mock-up spectrum.

## CONCLUSION

The following recommendations for non-linear dynamic analyses of crane bridges have emerged following the SOCRAT benchmark. Both the participants and the steering and expert committees agreed upon the following:

1. Due to the significant influence of i) friction between the wheels and the rails and ii) initial position of the bridge, it is recommended that a sensitivity study is carried out:
   - on the friction coefficients: within a representative range of values, considering an asymmetry in the distribution of friction coefficients, and considering bi-axial sliding.

- on lateral gaps between faces of the wheels and rails
- on different initial positions of the crane bridge
- on material properties
- on damping (characteristic values and modelling strategies)

This will provide a better understanding of the effect of these parameters on the behaviour of the crane bridge and mostly allow the identification of the envelope configuration or a set of configurations exploring the uncertainty range.

2. The reduced-size models such as those with fewer elements, and when they are sufficiently physically representative, can provide relevant results in terms of the general behaviour of the overhead crane bridge and therefore could be used to explore the uncertainties highlighted above.
3. Given the fact that horizontal support excitations causing rocking movements of the crane bridge (and thus different vertical excitations at each support) may lead to the wheels uplift, it is recommended to take into account the vertical motion imposed at the supports, at least considering rigidly bound supports (rigid body) but imposing rotational motion and vertical motion (in addition to horizontal motion) to the rigidly bound supports, at best by imposing the differential movement on each support (multi-supported), or by any other relevant mean.
4. If the calculation method retained is on a modal basis, it is necessary to consider both rigid body modes as well as the structural modes. In this case, it is important not to overdamp the rigid body modes. For the same reason, when calculations are performed through direct integration with Rayleigh damping, the coefficient proportional to the mass matrix should be removed as soon as the system is allowed to slide.
5. According to the results provided by the benchmark participants, it appears that local dissipative phenomena such local shocks or frictional sliding should be described by means of nonlinear contact laws, even simplified ones. However, most of efforts should be put on how to calibrate the input parameters of the model and how to describe the boundary conditions.

A best engineering practice should consist in simulating the crane bridge seismic behavior within the framework of a graded approach. Accordingly, the practitioners should first build a model that allows to describe accurately the boundary conditions such as the supporting plates, the load cells and the connection with the civil support (building). Second, assuming a linear behavior, modal analysis should be performed to estimate the modal properties of the mock-up and performing a linear seismic analysis of the model. Third, transient non-linear analysis needs to be performed by setting up friction coefficient considering a low damping ratio (for rigid body modes) and considering reference values ranging between 0.2 – 0.3, and including other relevant non-linearities (contact modelling for instance).

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