Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Special Session: Overview of the work done in the OECD SOCRAT benchmark

NUMERICAL SIMULATIONS OF THE NONLINEAR SEISMIC INTERACTION OF BRIDGE CRANE COMPONENTS IN THE SOCRAT BENCHMARK

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ABSTRACT

The benchmark SOCRAT (Seismic simulation of Overhead CRAne on shaking Table) is an international research program organised by the OECD-NEA (Nuclear Energy Agency) in collaboration with IRSN (Institut de Radioprotection et de Sûreté Nucléaire) and EDF (Electricité de France); see Geodynamique & Structure (2020). The main objective of the SOCRAT benchmark is to identify the best modelling practices of crane bridge devices under seismic excitations. The benchmark participants have to perform computational simulations of an experimentally tested crane bridge. The expert team from ENSI and Stangenberg & Partners (SPI) uses the structural analysis software SOFiSTiK (2020) to create a finite element model of the crane bridge model with shell elements for the load-bearing components. Appropriate modelling of the contact between the wheels and the rails is of primary importance for simulating the nonlinear behaviour of the trolley and the crane bridge. The wheel-rail contact is modelled by so-called moving springs, which – besides their local variability – take into account the nonlinear effects of gaps, exclusive transmission of compressive forces and transverse force transmission by means of friction. The finite element model characterised and calibrated in the first stage of the benchmark was used in the second stage to blindly predict the behaviour of the crane bridge model in the event of high-intensity earthquakes. This report deals with the numerical simulations performed in both phases of the benchmark and the conclusions with respect to the predictive ability of the model in deriving validated design requirements for bridge cranes under seismic loads.

INTRODUCTION

Bridge cranes are part of almost every nuclear facility. Due to their high hazard potential, these cranes have to be designed in such a way that safety-relevant system parts and structures are not impaired in the event of an earthquake to such an extent that they no longer fulfil their safety-related tasks. Modelling the mechanical behaviour of such a device under seismic load is a challenging scientific and engineering exercise, due to the importance of contact dissipative phenomena such as friction, sliding and impacts in determining their dynamic response.

Aiming to enhance the knowledge on the mechanical behaviour of this equipment, OECD-NEA, IRSN and EDF initiated the international research program SOCRAT as a benchmark open to interested experts; see Geodynamique & Structure (2020). The objective of the SOCRAT benchmark is to identify the best modelling practices of crane bridge devices and relevant failure criteria. An experimental campaign on a simplified 1/5 scaled model of an overhead crane with a 22.5 m long crane bridge (see Figure 1) was carried out in 2015 on the shaking table of the French Sustainable Energies and Atomic Energy Commission (CEA) and produced a large experimental database. These data are used for characterising and calibrating the modelling assumptions in the first stage, and for assessing the predictive capabilities of the simulations at high seismic intensities in the second stage. The benchmark participants were asked to perform computational simulations of the experimentally tested overhead crane mock-up.

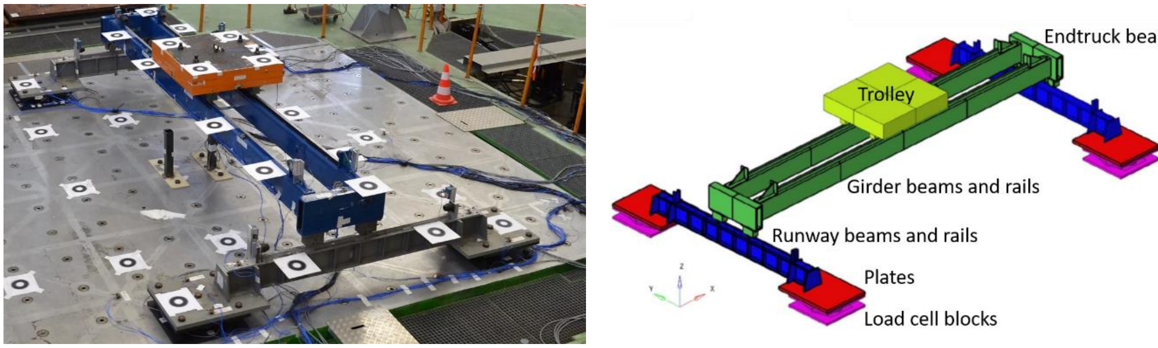


Figure 1. Mock-up on shaking table (left) and CAD model (right) (Geodynamique & Structure, 2020).

DESCRIPTION OF THE SOCRAT BENCHMARK

In the benchmark project SOCRAT, numerical simulations of the dynamic behaviour of a crane bridge under earthquake excitations are carried out. A selection of the measured data from tests performed on a 1/5 model of a double-girder overhead crane on a shaking table serves as a basis for comparison. The mock-up shown in Figure 1 is a simplified 1/5 scaled model of a 22.5 m long overhead crane bridge consisting of a trolley, rails, and wheels, two girder beams, two endtruck beams, two runway beams, and four load cell blocks (included in the supports between the shaking table and the runway beams). Besides the load cells, the mock-up is equipped with accelerometers and displacement sensors.

The first stage of the SOCRAT benchmark comprises three exercises on modal calibration of the crane bridge mock-up and some of its components, and three additional exercises on transient analyses for the calibration of friction coefficients, damping ratio, local shocks, as well as a high-level calibration. Stage 2 includes five exercises with blind nonlinear numerical simulations of the mock-up under high-intensity seismic loadings without knowledge of the experimental results. Apart from the different input signals for seismic excitation, these exercises differ in terms of the positions of the trolley and the crane bridge (centred or decentred; see Figure 2) and the possibility of the wheels of trolley and crane bridge to roll on the rails or not (mixed or sliding configurations; see Figure 3). In the case of wheels fixed to their supports, they can only slide on the rails depending on the friction conditions.

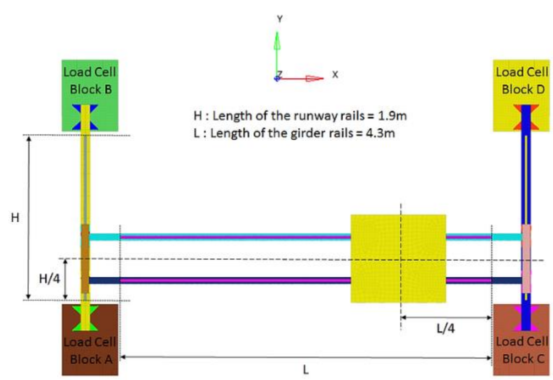


Figure 2. Decentred mock-up configuration (Geodynamique & Structure, 2020).

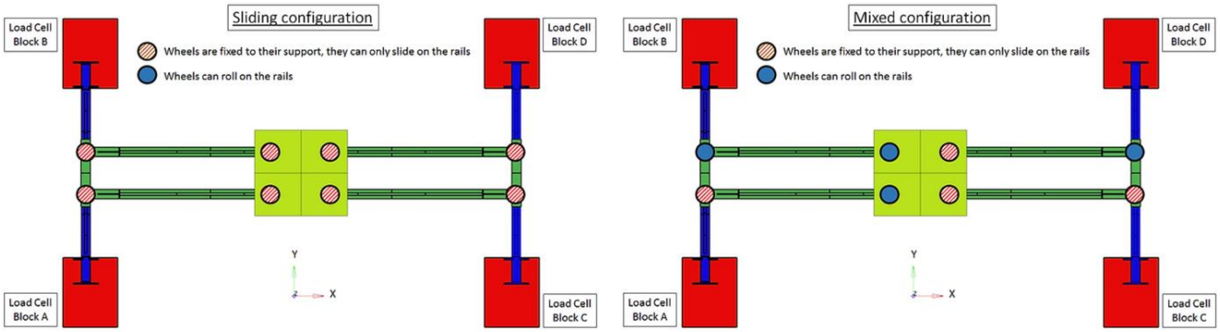


Figure 3. Mock-up configurations related to rolling and sliding of the wheels on the rails (Geodynamique & Structure, 2020).

NUMERICAL SIMULATIONS

Numerical Analysis Methods

The team from ENSI and SPI uses the structural analysis software SOFiSTiK (2020) for the numerical analyses of the SOCRAT benchmark. The eigenfrequencies and eigenmodes are determined by means of linear analyses of the independently created finite element (FE) models to check the correct modelling of the mock-up and its parts. The numerical simulation of the seismic tests is carried out using nonlinear time history analyses. The analysis of nonlinear effects in SOFiSTiK is done by iterations using a modified Newton method; i.e. an implicit integration scheme is used.

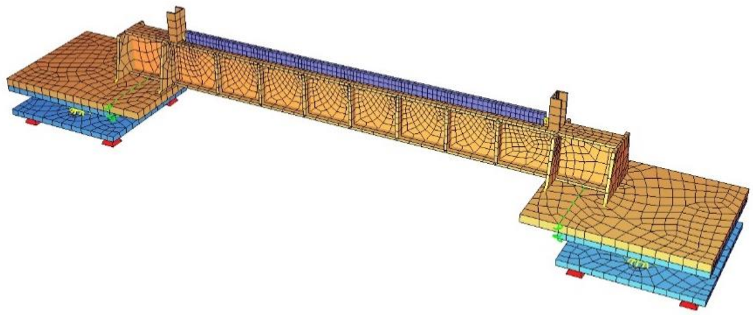
Numerical Simulations of Exercises in Stage 1

The first three exercises are devoted to the modal calibration of the load cell block measuring the support forces (exercise 1), the runway beam (exercise 2), and the crane bridge (exercise 3); see Figure 1. During the experimental campaign, white noise signals and hammer shocks were applied, and frequencies were calculated by Fourier transform (FFT) and transfer function.

One load cell block consists of squared 30 mm thick upper and lower steel plates with a side length of 650 mm, as well as four cylindrical load cells with diameters of 175 mm and heights of 110 mm that connect the two plates. The stiffness of a single load cell is defined by a stiffness matrix given by the manufacturer. The load cells are modelled using coupled spring elements whose stiffness is adjusted according to the elements of the given stiffness matrix.

The partial model of the crane system examined in exercise 2 is a runway beam with the two plates welded to it, supported by the two load cell blocks underneath. Figure 4 contains the generated shell element model and a table with eigenfrequencies. The calculated eigenfrequencies show a good agreement with the data determined in the tests. The transient analyses for white noise signals in transverse, longitudinal and vertical directions of the runway beam implied that its vibration behaviour is captured quite well.

The object of exercise 3 is the modal characterisation of the complete crane bridge mock-up on its four load cell blocks. For this exercise, the trolley was locked on the girder beams and the endtruck beams were locked on the runway beams with clamp joints in order to achieve a linear system. The task was to determine the eigenfrequencies of the system and to carry out transient analyses for a 3-directional white noise signal. Figure 5 contains the SOFiSTiK FE model mainly consisting of shell elements. The main eigenmodes in the three coordinate axes are shown in Figure 6. The calculated eigenfrequencies agree well with the experimentally derived values. The transient analyses confirm this result.



Eigenmode	Experiment	Analysis
[Hz]		
f_1	57.1	56.7
f_2	108.8	108.7
f_3	115.2	123.2
f_4	122.2	124.4

Figure 4. FE model of the runway beam and eigenfrequencies.

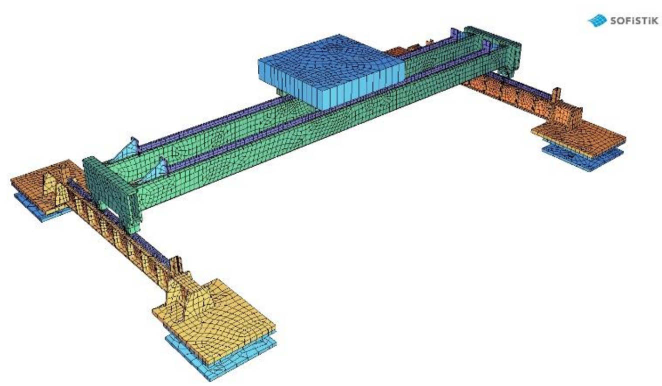
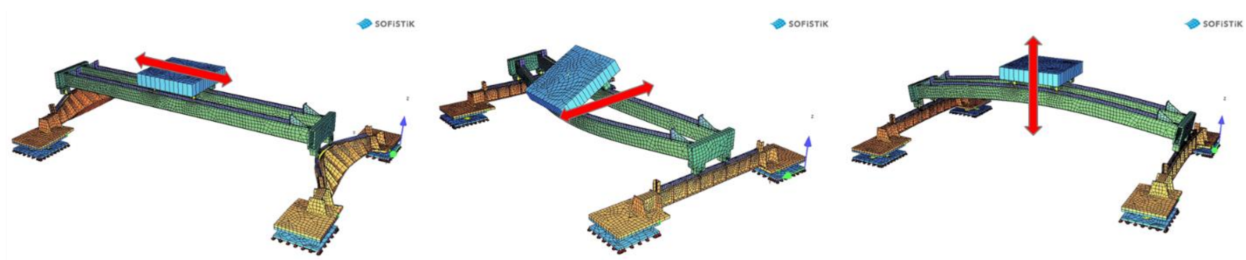


Figure 5. FE model of the crane bridge mock-up.



$f_{x,cal}$ = 7.8 Hz
$f_{x,exp}$ = 7.6 Hz
$DEV_{x,cal}$ = +3%

$f_{y,cal}$ = 7.7 Hz
$f_{y,exp}$ = 8.3 Hz
$DEV_{y,cal}$ = -7%

$f_{z,cal}$ = 13.1 Hz
$f_{z,exp}$ = 13.3 Hz
$DEV_{z,cal}$ = -2%

Figure 6. Fundamental eigenmodes of the crane bridge model.

The task of exercise 5 is to calibrate the coefficients of friction between wheels and rails. Transient analyses are performed, which take into account contact dissipative phenomena such as friction, sliding and impacts in determining the nonlinear dynamic response of the crane bridge. Friction forces arise between the wheels of the trolley and the rails of the girder beams as well as between the wheels of the crane bridge and the rails of the crane runway beams (see Figure 7). This behaviour depends on whether the wheels can roll or are locked and therefore can only slide on the rails. In addition to the longitudinal direction, sliding is also possible in the transverse direction of the rail. Due to the gaps between the wheel flanges and the rails, which are just a few millimetres in size, the wheels can hit the rails.

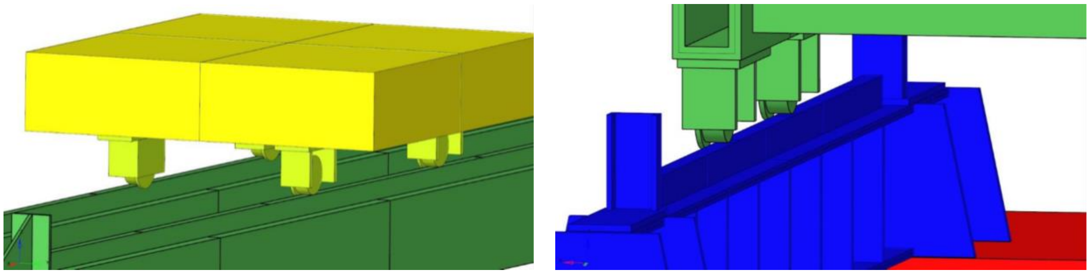


Figure 7. Positions of the trolley wheels (left) and crane bridge wheels (right) (Geodynamique & Structure, 2020).

The FE model uses moving spring elements searching for contact nodes in each time step to include the wheel-rail contact. Vertical springs represent the wheel-rail contact and transverse horizontal springs the flange-rail contact (see Figure 8). Friction coefficient and gap width as well as damping ratio can be set individually.

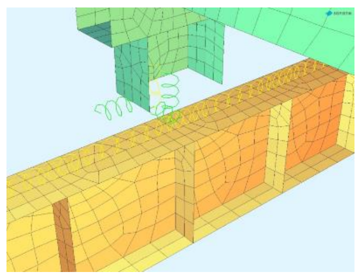


Figure 8. Simulation model for wheel-rail contact.

Exercise 5 requires transient analyses for the unidirectional pulses shown in Figure 9, two of them with the sliding wheels configuration and the third on the right with the mixed wheels configuration according to Figure 3. Calibrating the coefficients of friction and the damping ratio of the system required a series of iterative calculations. Figure 10, Figure 11, and Figure 12 document the calculated time histories of relative displacements between the trolley wheels and the girder beams, and between the endtruck wheels of the crane bridge and the runway beams in comparison to the measured time histories.

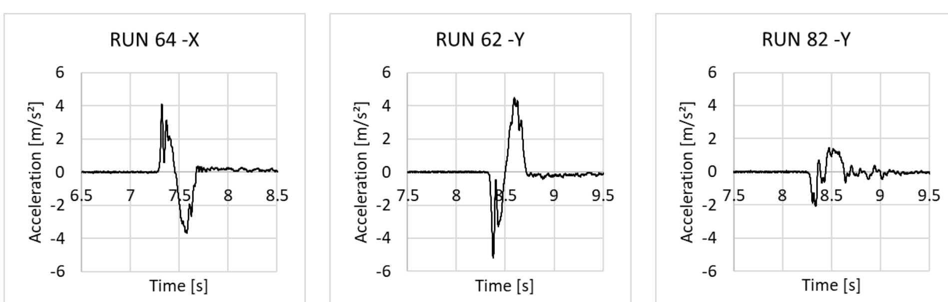


Figure 9. Unidirectional accelerations in exercise 5.

A pulse loading in the x-direction (transverse to the crane runway) is applied to the crane bridge with the centred sliding wheels configuration (see Figure 3) in Run 64. The best agreement between calculated and measured values is obtained with coefficients of friction for the trolley wheels between $\mu = 0.29$ and $\mu = 0.36$ (see Figure 10). As the time histories of the relative displacements show, phases with changing displacements alternate with phases with constant displacements. In the experiment, the trolley only begins to slide when the direction of the pulse changes (see Figure 9). An initially higher static friction presumably contributes to this behaviour. Since the numerical model cannot differentiate between static and sliding (dynamic) friction, such behaviour is not simulated in the calculation. Another possible explanation is that the wheels of the endtruck, and consequently the entire crane bridge, start sliding earlier (out of plane) than the wheels of the trolley. As a result, the trolley would only slide on the crane bridge (in plane) when the gap of the endtruck wheels (horizontal distance between wheel flange and rail) is closed (see Figure 7 left).

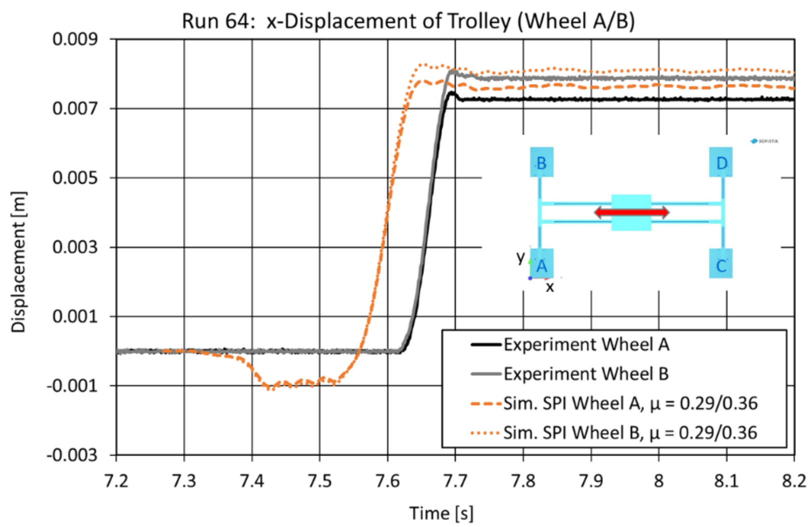


Figure 10. Exercise 5, Run 64, Sliding configuration, Relative displacements of trolley.

In Run 62, a pulse loading in the y-direction (direction of the crane runway) acts on the crane bridge with the sliding wheels configuration. Asymmetrical displacements of the left and right endtruck beams indicate that the crane bridge rotates around the vertical axis (see Figure 11). Different coefficients of friction for the wheels of the endtrucks on both runways between μ = 0.14 and μ = 0.17 lead to the best agreement between calculated and measured displacement values.

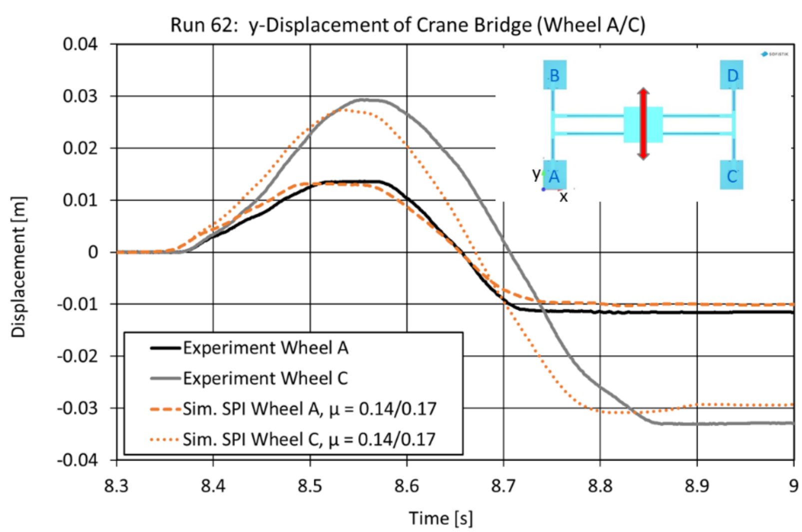


Figure 11. Exercise 5, Run 62, Sliding configuration, Relative displacements of crane bridge.

In Run 82, a different pulse loading in the y-direction acts on the crane bridge with the mixed configuration of locked (sliding) and free (rolling) wheels according to Figure 3. Asymmetrical displacements of the left and right endtruck beams occur here as well (see Figure 12). The rolling wheels friction coefficient was set to μ = 0.01. The values for the sliding wheels had to be chosen quite lower than in previous runs in order to match the measured displacements on both crane runways (μ = 0.07 on one side and μ = 0.10 on the other side). Presumably, the damages suffered by the rails during the tests result in a variation of the friction coefficient from one run to another.

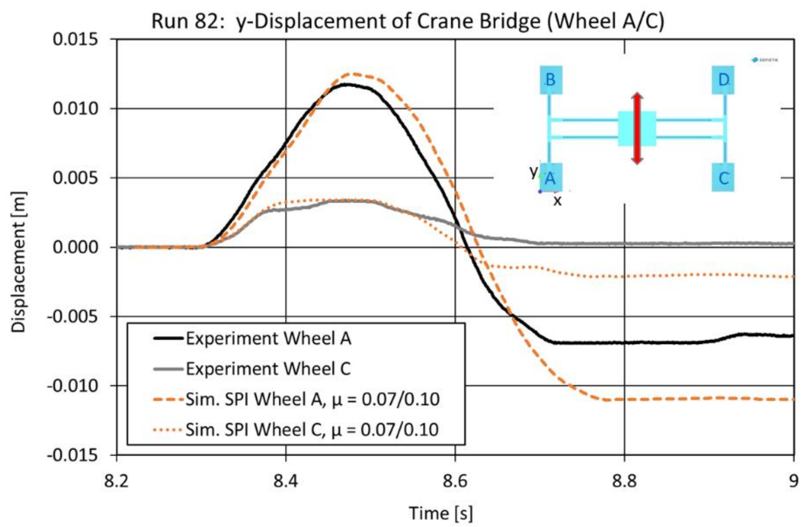


Figure 12. Exercise 5, Run 82, Mixed configuration, Relative displacements of crane bridge.

The objective of exercise 6 is to analyse the modelling of the local shocks (uplift) between the wheels and the rails. The acceleration imposed by the shaking table is characterised by a 3-directional seismic signal (Peak Ground Acceleration PGA = 1g). The sliding configuration (wheels not fixed to the rails with the possibility of sliding, jumping, but not rolling) is used in combination with eccentric positions of the trolley and the crane bridge according to Figure 2. The magnitude of the vertical displacements is well predicted by the numerical analysis. However, the provided experimental input and output signals were not suitable for studying the uplift phenomenon. Hence, it was not possible to perform a calibration of the local shock parameters in this exercise. Figure 13 shows the relative horizontal displacement time histories of the endtruck. In the numerical analysis, different coefficients of friction for both sides of the trolley (μ = 0.26 / 0.3) and the endtrucks (μ = 0.16 / 0.24) are assumed. However, the model could not simulate the rotation around the z-axis occurred in the experiment in a good quality.

The last exercise of the benchmark stage 1 (exercise 7) is dedicated to a high-level calibration by applying a 3-directional seismic signal (PGA = 0.5g) and considering the centred wheel sliding configuration (see Figure 3). Assuming the same coefficients of friction as in exercise 6, the displacement time histories of the endtruck shown in Figure 14 agreed reasonably well with the measurements.

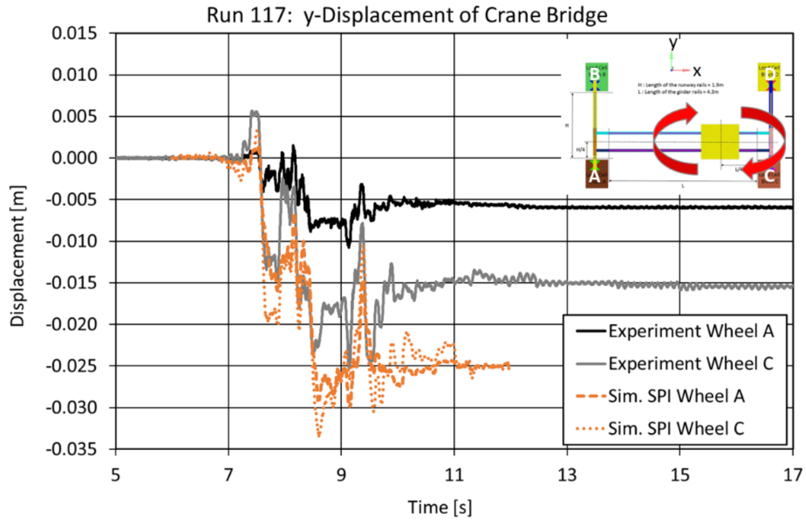


Figure 13. Exercise 6, Run 117, Sliding configuration, Relative displacements of crane bridge.

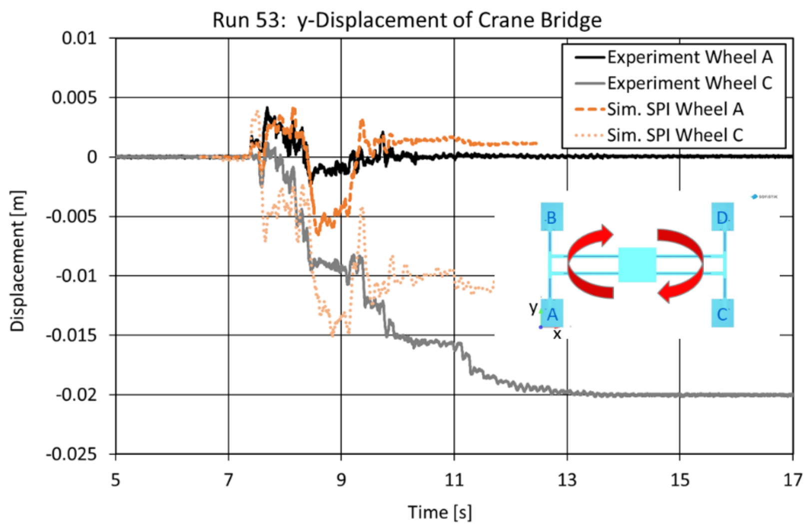


Figure 14. Exercise 7, Run 53, Sliding configuration, Relative displacements of crane bridge.

Numerical Simulations of Exercises in Stage 2

Stage 2 of the benchmark comprises five exercises (8 to 12) with blind, nonlinear simulations of the mock-up under high-intensity seismic loadings. The exercises include centred and decentred positions of trolley and crane bridge, as well as sliding and mixed wheels configurations according to Figure 2 and Figure 3. The computations for the blind predictions in stage 2 are performed with the model calibrated based on the comparison of the results of stage 1 (exercises 5, 6 and 7) assuming different coefficients of friction for both sides of the trolley ($\mu = 0.26 / 0.3$) and the endtruck ($\mu = 0.16 / 0.24$). The assumption of different coefficients of friction is based on the objective of being able to numerically simulate the observed twisting of the trolley and the crane bridge.

The calculation results require a more in-depth evaluation compared to the measurement results from the individual vibration table tests, which were made available to the benchmark participants after the calculation results had been transmitted. The presentation at the conference will report on the detailed evaluation of the accelerations, displacements and support forces. At this point, results from exercise 10 are presented as an example. The acceleration imposed by the shaking table in Run 112 is characterised by a seismic signal in the horizontal directions (PGA = 1.5g). The sliding configuration is used in combination with eccentric positions of the trolley and the crane bridge according to Figure 2.

Figure 15 illustrates the good agreement between the calculated and measured accelerations of the runway beam in the direction of the crane bridge. The twisting of the crane bridge, which is only slight despite the eccentric positions of the trolley and the crane bridge, is higher than predicted by calculation (see Figure 16). Nevertheless, the calculated relative displacements of the crane bridge show a satisfactory agreement with the measured data in view of the uncertain determination of the friction conditions.

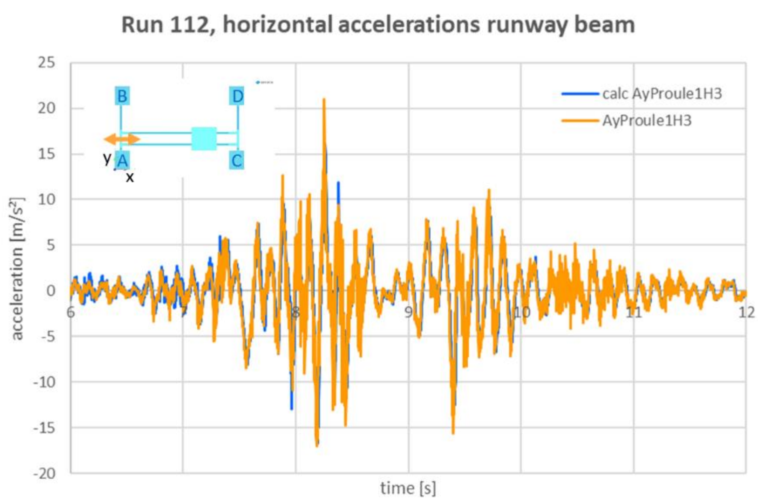


Figure 15. Exercise 10, Run 112, Sliding configuration, Accelerations of runway beam.

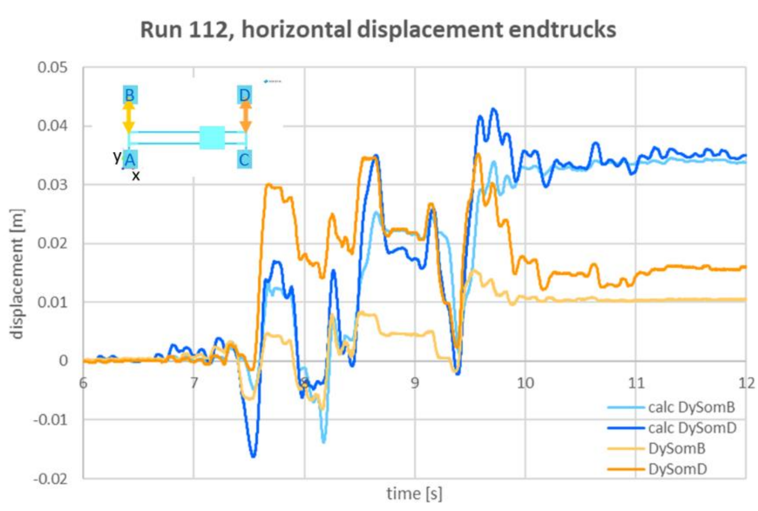


Figure 16. Exercise 10, Run 112, Sliding configuration, Relative displacements of crane bridge.

CONCLUSIONS

As part of the process to determine the best modelling practices of crane bridges within the SOCRAT benchmark, in the first stage a series of exercises for characterising and calibrating the simulation model is carried out. The finite element model characterised and calibrated in the first stage of the benchmark is used in the second stage to blindly predict the behaviour of the crane bridge model in the event of high-intensity earthquakes.

One of the most important findings is that the results of the numerical simulations depend strongly on the assumed values for friction, damping and geometric properties like gaps between wheel flange and rail. The parametric calibration analyses have shown that it is possible, with limitations, to find combinations of coefficients of friction with good agreement between numerical simulation and experiment. It would be desirable to be able to take into account the dependencies of the coefficients of friction on the sliding speed (static or sliding friction) and on the directions of action in the numerical model. Moreover, the effect of the gaps between wheels and rails on the dynamic behaviour of the crane bridge requires further investigation.

The evaluation of the blind nonlinear simulations carried out so far shows that the single set of locked wheel friction coefficients used for all configurations and excitations resulted in a variable close agreement of calculated and experimental results. The influence of the identified limitations on the predictive ability of the model in deriving validated design requirements for bridge cranes under seismic loads requires further investigation. In this sense, the detailed evaluation of the accelerations, displacements and supporting forces from the blind numerical predictions in stage 2 of the benchmark will be reported in the presentation at the conference.

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