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# MODELLING OF AN OVERHEAD CRANE UNDER SEISMIC EXCITATIONS (SOCRAT)

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## ABSTRACT

A methodology to simulate bridge cranes under seismic loading is developed based on the activities carried out in the SOCRAT (Seismic simulation of Overhead CRAne on shaking Table) benchmark. Its first stage is the calibration of the models based on the experimental results, which, in a second stage, are used for blind predictions of non-linear scenarios at high seismic intensities. The modelling approach developed by the team formed by ENSI and Principia/SPI is described in the paper. A finite element model is constructed, mainly using shell elements. The interactions with the rails are represented by two-node connector elements type "slot" and "translator" with a Coulomb frictional behaviour, and "stop" constraints are employed to capture gaps and uplifts. High intensity seismic scenarios are solved with an explicit dynamic procedure.

## INTRODUCTION

Modelling the mechanical behaviour of crane bridges under seismic loads is a challenging exercise due to the importance of contact dissipative phenomena such as friction, sliding and impacts in their response. The SOCRAT (Seismic simulation of Overhead CRAne on shaking Table) benchmark is an international research program organised by OECD-NEA (Nuclear Energy Agency, 2020), IRSN (Institut de Radioprotection et de Sûreté Nucléaire), and EDF (Electricité de France) to identify the best modelling practices for crane bridge devices, and the relevant failure criteria. The benchmark is based on data produced in an experimental campaign conducted on a 1/5 scale model of a 22.5 m overhead bridge crane on a shaking table. The mock-up consists of a trolley supported by two girder beams that may roll on two runway beams; four load-cell blocks are included in the supports between the shaking table upper plate and the crane bridge mock-up.

A team formed by engineers from ENSI (Swiss Federal Nuclear Safety Inspectorate), Principia (Spanish consulting firm) and Stangenberg & Partners (German consulting firm) has participated in the benchmark. In a first stage the models are calibrated using the experimental results which, in a second stage, are used for blind predictions of non-linear scenarios at high seismic intensities.

The approach followed by the ENSI/Principia/SPI team has consisted in generating a representative finite element mesh and activating solution strategies of progressively increasing complexity, as demanded by the phenomena to be modelled. Thus, modal analyses have been undertaken, followed by direct implicit integration in the time domain and, finally, by explicit integration when contacts and other nonlinearities became dominant. The known experimental results are used first to calibrate some parameters of uncertain value, particularly friction coefficients. Once those parameters have been calibrated, the model is used for making blind predictions of the response of the crane bridge in strongly non-linear scenarios at high seismic intensities.

## ASSUMPTIONS AND MODEL DESCRIPTION

A finite element model has been constructed using Abaqus (SIMULIA, 2021) with mainly reduced integration, linear shell elements (Figure 1). It has about 52,000 elements and 53,000 nodes; the types of elements used are given in Table 1.

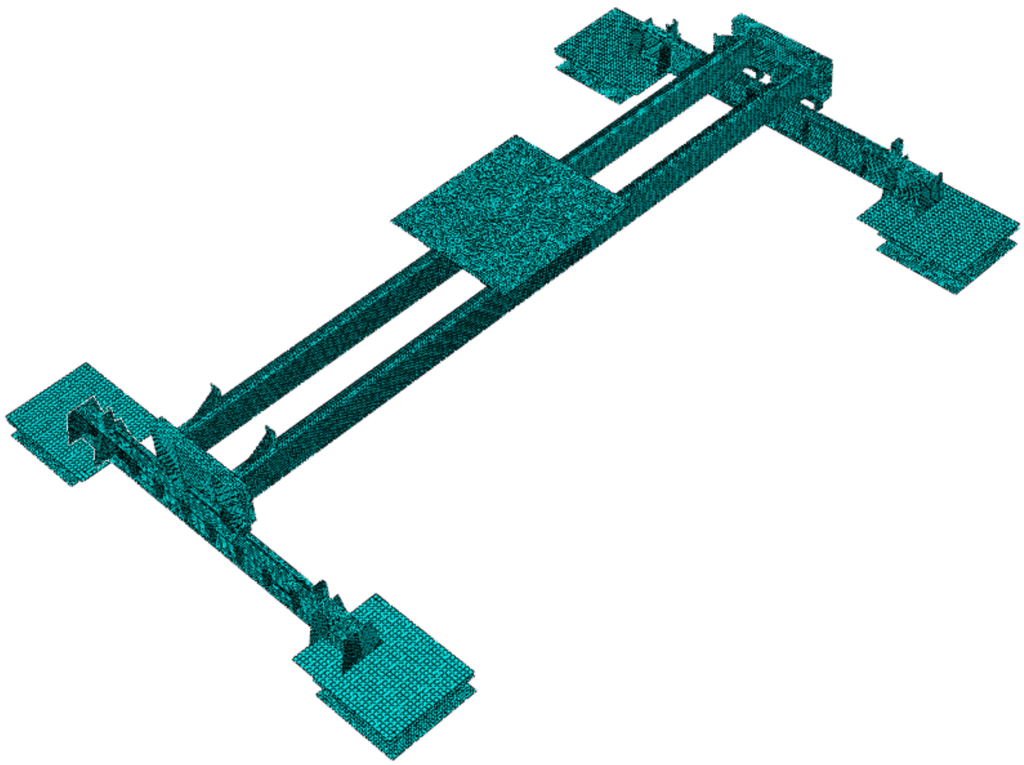

Figure 1. Finite element model for modal analysis

| Part | No. of instances | No. of elements | Abaqus element type |
|---|---|---|---|
| Trolley | 1 | 3760 | S4R |
| Girder beams | 1 | 19976 | S4R |
| Wheels | 8 | 1 | CONN3D2 |
| Runway beam | 2 | 8230 | S4R |
| Plate | 4 | 616 | S4R |
| Thick plate | 8 | 1178 | S4R |
| Load cell | 16 | 1 | CONN3D2 |

Table 1. Mesh characteristics of the modal model

Each load cell, connecting the upper and lower plates of the cell block, is generated using a "connector" element to the stiffness matrix provided by the benchmark organisers; connector elements parametrise the relative motion of two nodes to create kinematic constraints or to define a specific behaviour exchanging self-balanced forces and moments between both nodes. Point masses are located at the load cells and wheels and coupled to the structure through kinematic couplings.

Linear-dynamic calculations (eigenvalue and transient modal-dynamic procedures) are initially performed to validate the natural frequencies of the load cell blocks, runway beams, and full assembly (with blocked wheels) by comparison with the experimental results produced in hammer tests and low-intensity dynamic base excitations.

Friction coefficients are calibrated for the wheel-girder and wheel-runway contacts using the experimental results from pulse excitations; no distinction is made between static and kinetic friction coefficients. The wheels are not included in detail in the model, and the interactions with the rails are represented by connector elements type "slot" with a Coulomb frictional behaviour. The uplift of the trolley (simplified as a rigid body with the appropriate mass and rotational inertia) and the lateral gap of the wheels and runway beams are also represented by connector elements, of types "slot" and "translator", with contact-enforced stops in the component of relative motion. In some of the configurations all wheels are fixed to their supports and can only slide on the rails, while in others some can also roll on the rails.

Strongly nonlinear behaviours, such as frictional contacts, preclude modal analyses, and a direct implicit integration may experience some transient convergence issues. Thus, an explicit solver was deemed more robust for the high-intensity excitations, even if it requires millions of time steps to span the history of excitation and the dynamics of the problem preclude the use of mass scaling.

Gravity is introduced in a first quasi-static step, then histories of accelerations are imposed at the boundaries. In the explicit simulations, a band-limited damping ratio is introduced; unlike stiffness proportional damping, which creates an additional damping stress proportional to the total strain rate, the band-limited damping creates damping stresses proportional to the rate of the filtered constitutive stress at each integration point.

The outputs generated are absolute accelerations (with an antialiasing filter at the output frequency to reduce numerical noise), cell loads, and relative displacements.

## MODAL ANALYSES

Modal analyses were performed in the previous model to determine the modal shapes and associated frequencies. This of course is only applicable when all the wheels are fixed to the rails and, therefore, there is no sliding, rolling or uplift separation. The results can be seen in Figure 2, which present the first two modes of the crane bridge in those conditions. As indicated in the figure, the more relevant frequencies are 7.9 Hz and 8.6 Hz.

The previous model was then used to determine the response to a specified white noise (run 33, as per the naming by the benchmark organisers). The results calculated at the chariot in the three directions are compared with the experimental observations in Figure 3, in terms of the power spectral density of accelerations (ASD). As can be noticed, the comparison is quite satisfactory, with some deviations at the higher frequencies in the horizontal directions.

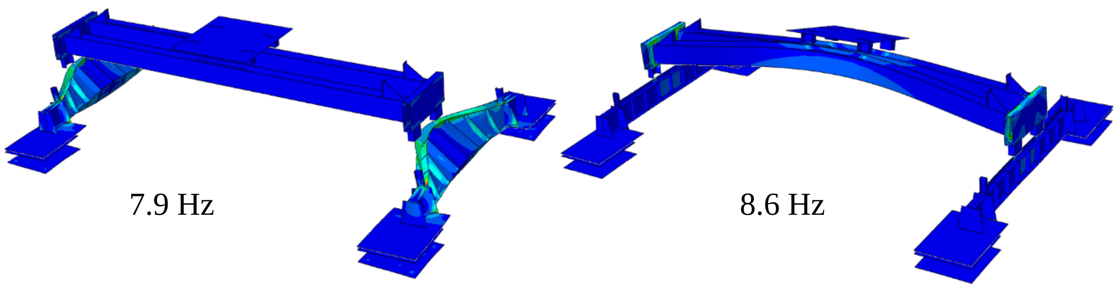


Figure 2. Modes for fixed conditions

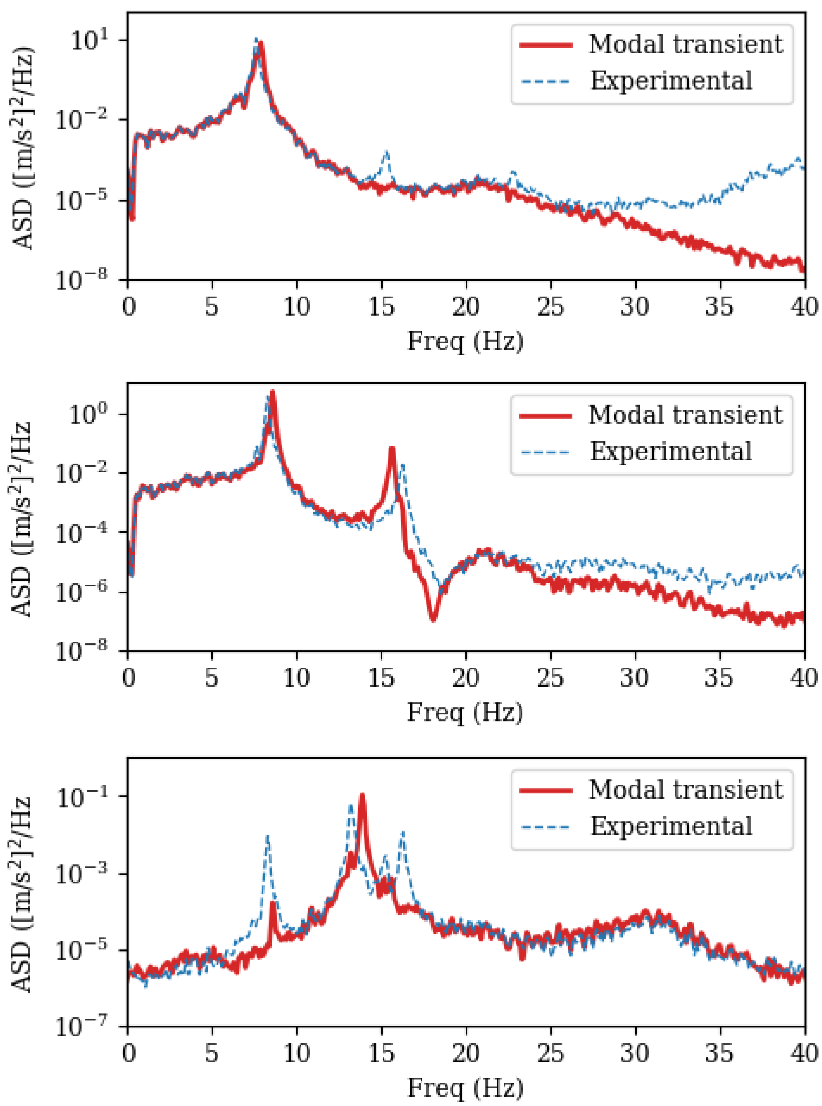


Figure 3. ASD at the chariot (run 33)

## CALIBRATION OF FRICTION COEFFICIENTS

Following the first check on the linear situation, an exercise was conducted to calibrate the relevant friction coefficients. This was performed by reproducing the response when the chariot is centred in the girder rails, the girder rails are centred in the runway rails, and all 8 wheels can slide but not roll.

The problem was solved by implicit integration; the results of the calibration appear in Figure 4 for run 62 and Figure 5 for run 64. The difference between the two runs is that the input is applied along the Y direction in the former and along the X direction in the latter; the girder beams are parallel to the X axis and the runaway beams are parallel to the Y axis. Analyses were conducted with different values of the friction coefficients to try to achieve an optimal fit of the experimental results.

As can be seen in the displacement histories shown in the figures, the agreement is reasonable but not excellent. In any case, as a result of the calibration, the values of the friction coefficients that were considered more representative were 0.25 for the friction of the wheels with the runway rails, and 0.30 for that of the wheels with the girder rails. In case of rolling wheels, a friction coefficient of zero is used.

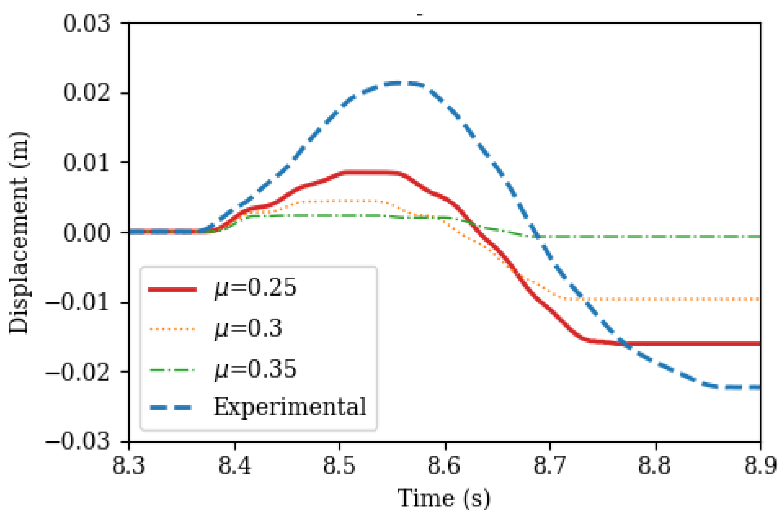


Figure 4. Transient analysis for calibration of friction wheel/runway (run 62)

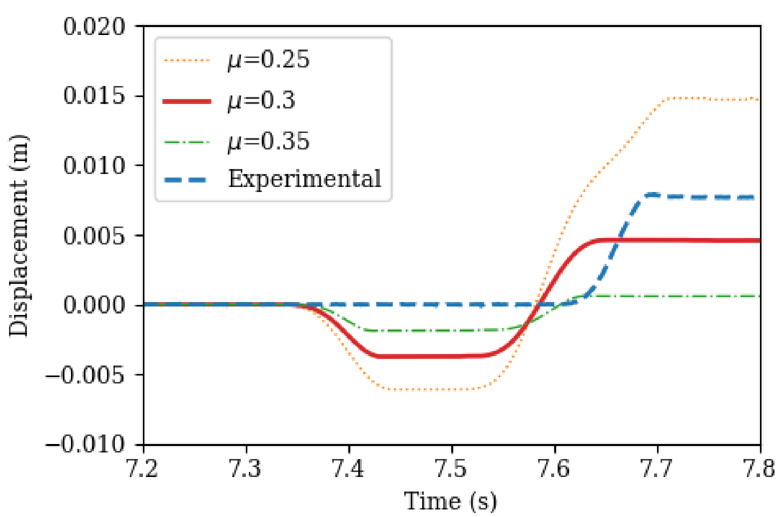

Figure 5. Transient analysis for calibration of friction wheel/girder (run 64)

## MODEL PREPARATION FOR THE SEISMIC SIMULATIONS

Having calibrated the friction coefficients, slight modifications were made to the model for the seismic calculations. Slot connectors were used to represent the wheels with or without friction. Additional translator elements were introduced in the girder beam wheels with a connector stop to represent the 7 mm gap. Connectors were also placed in the trolley to allow separation of the wheels from the rails when $a_z < -9.8$ m/s$^2$ ("slot" connector with connector stop). The connectors representing the wheel-rail interactions are schematically depicted in Figure 6.

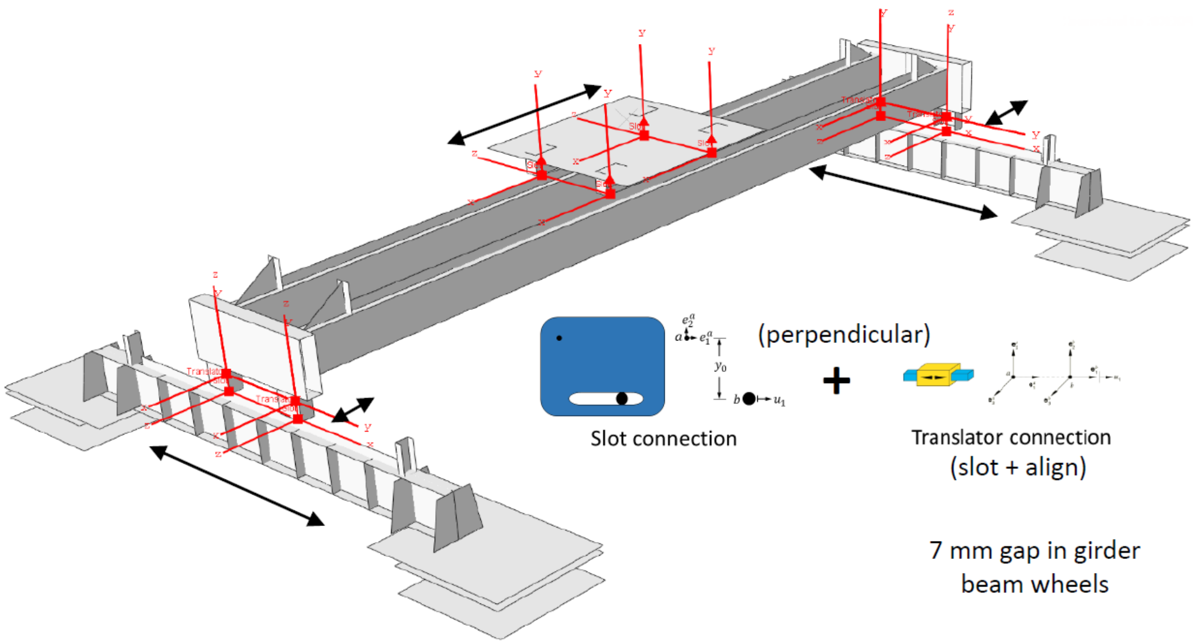


Figure 6. Connectors representing the wheel interactions, including gaps

The mesh was revised to be more suitable for the long explicit simulations, the resulting mesh had about 13,000 elements and 13,000 nodes. The specific characteristics of the mesh are presented in Table 2.

| Part | No. of instances | No. of elements | Element type |
|---|---|---|---|
| Trolley | 1 | 518 | S4R |
| Girder beams | 1 | 5007 | S4R |
| Trolley wheels | 4 | 1 | CONN3D2 |
| Girder wheels | 4 | 2 | CONN3D2 |
| Trolley uplift | 1 | 1 | CONN3D2 |
| Runway beam | 2 | 1094 | S4R |
| Plate | 4 | 154 | S4R |
| Thick plate | 8 | 572 | S4R |
| Load cell | 16 | 1 | CONN3D2 |

Table 2 Mesh properties of the explicit model

With this new mesh a simulation was conducted of run 53, which corresponds to a situation in which the chariot and beams are centred, and the wheels can slide but not roll. Gravity was first applied along 1 s, followed by an acceleration input over 30 s. The time step is automatically chosen by the program to ensure the stability of the explicit integration. A decision was made not to use mass scaling to avoid interfering with the dynamics of the problem.

The table motion applied in each run is introduced as an acceleration boundary condition at the attachment point of the bottom plate of the load cell blocks. The damping is defined with a fraction of critical damping of 1% for a frequency band between 3 Hz and 100 Hz. The damping stress is proportional to the rate of filtered constitutive stress at each integration point.

To capture the trolley separation from the rails, the arrangement shown in Figure 7 was used. The mass is distributed between the shell elements, which represent 10% of the total mass, and a reference point, connected to the shell, which has 90% of the total mass.

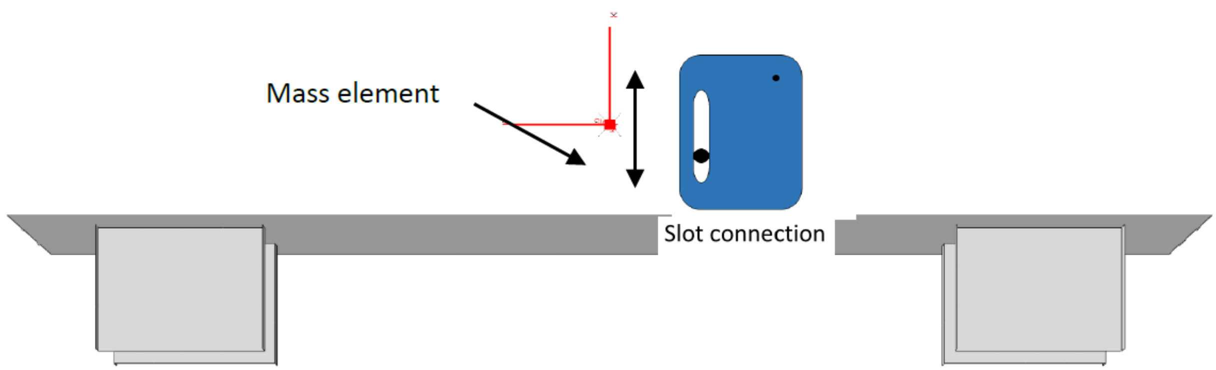


Figure 7. Modelling aspects to capture the trolley separation

Some results are reported below and compared with the experimental observations. Figure 8 shows the vertical accelerations of the chariot, which are reasonably consistent with the measurements. Figure 9 presents the horizontal displacements of the wheels, which match very well measured displacements.

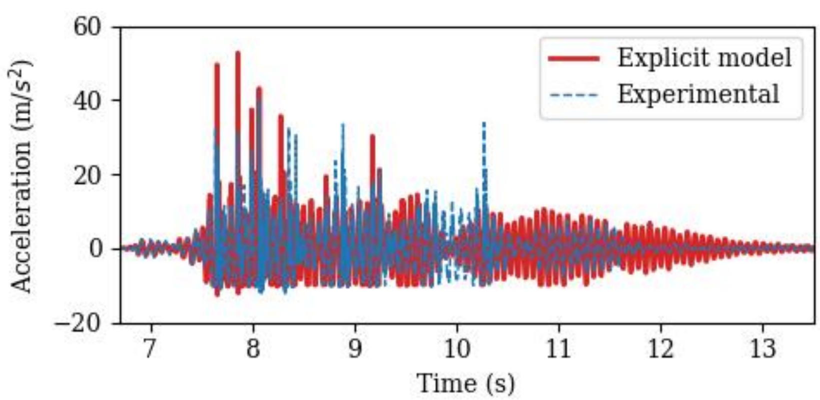


Figure 8. Vertical acceleration of the chariot for run 53

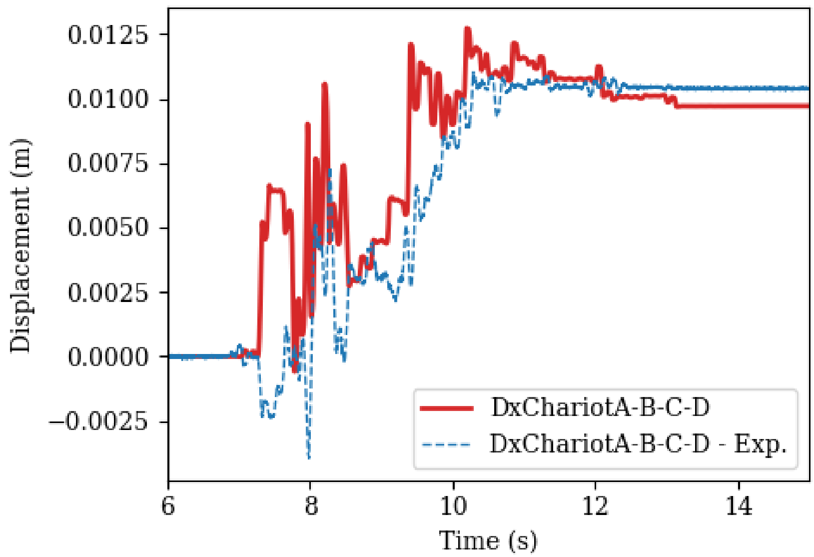


Figure 9. Chariot wheels displacements for run 53

## BLIND SIMULATIONS

Having performed the previous calculations, some for calibration and some for verification of the calibrated parameters, blind simulations were performed for the cases in which the measured results were unknown at the time of conducting the analyses. They were made available later, which allows including some comparisons in the present paper.

The blind simulations reported here correspond to run 118. It is a decentred configuration with mixed wheels (rolling and sliding). Qualitatively, similar results are obtained for the rest of blind test runs.

The calculated displacements for the chariot wheels are shown in Figure 10. The calculated displacements are one half of the measured ones and have the opposite sign. Much better is the agreement of the calculated and measured displacements of the wheels of the girder beams, which appear in Figure 11. Those displacements are large and the calculations reproduce well the experimental observations.

Some information on the measured forces was made available. This corresponds to data produced by the load cells in the chariot and allows making a comparison with the calculated values. Some selected comparisons are offered here. The histories of the longitudinal (along the X axis) forces measured in the four load cells are shown together with the calculated histories in Figure 12; as can be seen, the comparison can be considered reasonable. The same applies to the histories of the forces in the transversal direction (along the Y direction), which appear in Figure 13.

Based on the results shown, the predicted sliding histories of the wheels on the runway beams are deemed satisfactory in all the blind simulations. However, the sliding of the trolley is not very well captured, and the accumulated displacements are underestimated.

The above finding suggests that, for the girder beams, a lower value of the effective friction coefficient could have been more appropriate, perhaps closer to the value used for the runway beams.

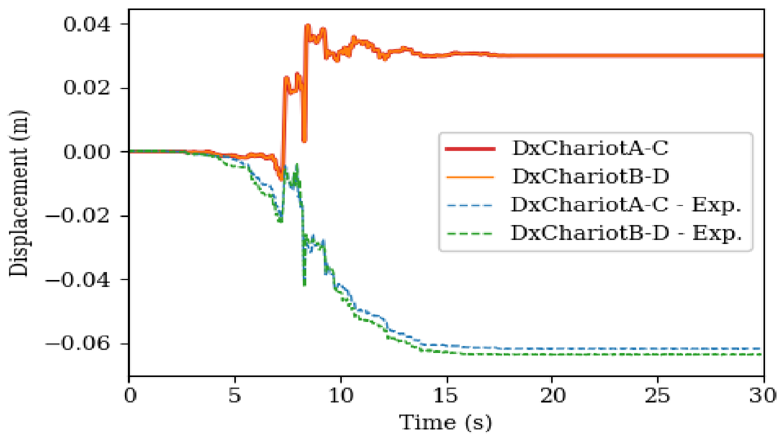


Figure 10 Chariot wheels displacements for run 128

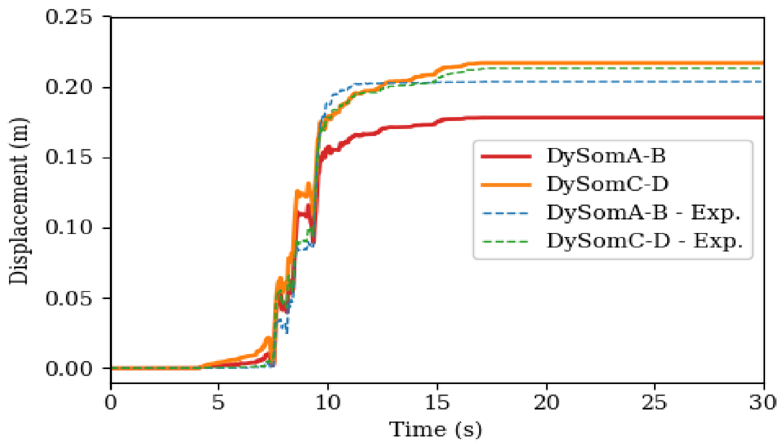


Figure 11 Girder beam wheels displacements for run 128

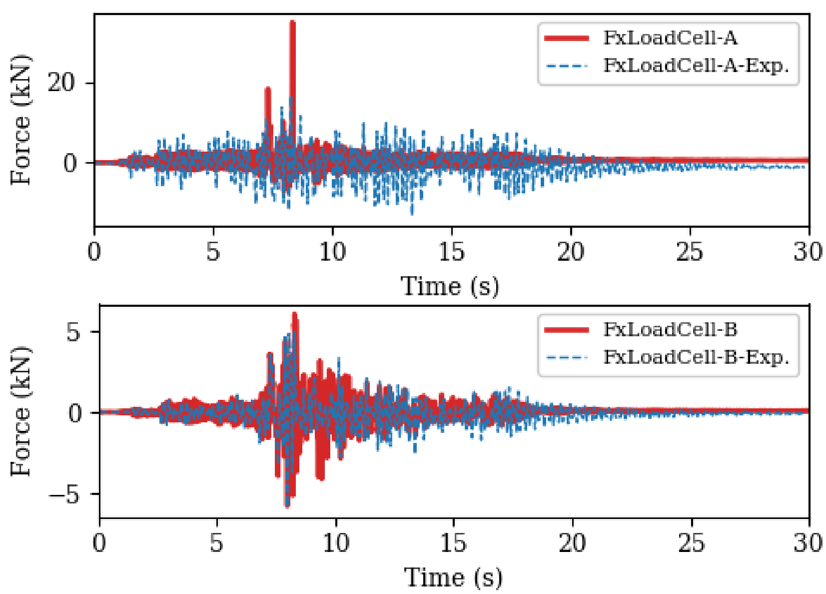


Figure 12 Longitudinal forces in cell blocks

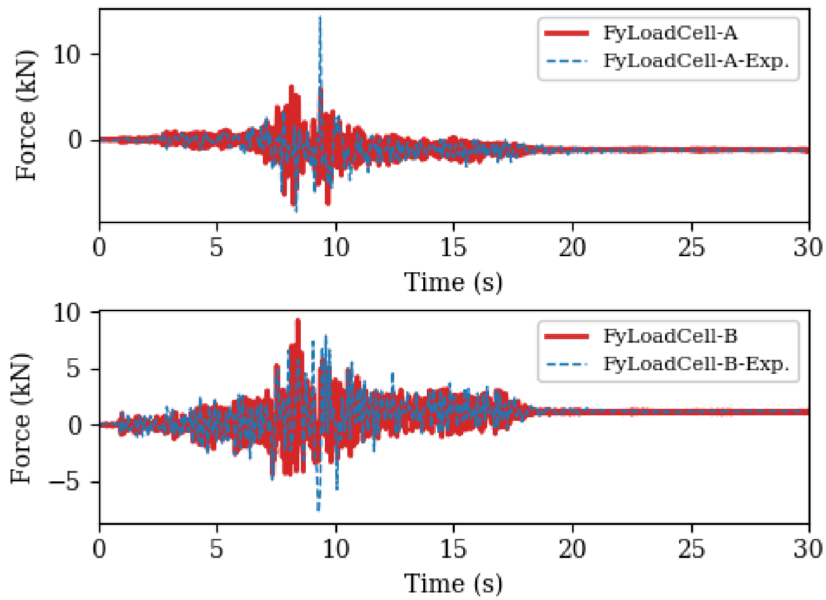


Figure 13 Transversal forces in the cell blocks

## CONCLUSIONS AND RECOMMENDATIONS

In the context of the activities carried out in the SOCRAT benchmark, a methodology has been developed to simulate the response of bridge cranes under seismic loading. The structure was represented by a finite element mesh of shell elements, and the interactions between different parts (wheels and rails, and for the loading cells) were simplified using connector elements. Explicit integration with Abaqus was used to determine the response of the model.

It was found convenient to build the models step-by-step, guided by the benchmark organisers, in a way that could be easily adapted to the different integration solvers: modal, implicit direct dynamics, and explicit. Whenever possible, the consistency of the results for different solvers was verified. This allowed employing the most suitable approach for each exercise and gaining knowledge for subsequent exercises even when the solver was changed.

The interaction between the wheels and the rails is a complex phenomenon. In the approach adopted, simplified interaction models with two-node connectors were used. More sophisticated models are possible, such as those including surface-to-surface contacts, but the tribological characterisation is difficult and the simpler models appeared more promising. The uplift of the trolley wheels and the gaps between the wheels and the runway beams were also modelled with connector elements.

Overall, the modelling activities undertaken are considered moderately successful. In spite of the difficulties posed by the various wheel-rail interactions, the order of magnitude of the main results is adequately estimated, even if not all the details of the calculations agree with the experimental observations.

## REFERENCES

Nuclear Energy Agency OECD/NEA (2020) “SOCRAT Benchmark. Seismic simulation of Overhead CRAne on shaking Table”, https://www.socrat-benchmark.org.
SIMULIA (2021) “Abaqus Analysis Documentation”, version 2021.