Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

THREE-DIMENSIONAL NON-LINEAR SEISMIC ANALYSIS OF BRIDGE CRANE USING HETEROGENEOUS ASYNCHRONOUS TIME INTEGRATOR

Sijia Li[1*], Brun Michael[2], Anthony Gravouil [3], Walid Larbi[4]

[1] Associate Professor, Structural Mechanics and Coupled Systems Laboratory, Conservatoire National des Arts et Métiers, 75003 Paris, France (sijia.li@lecnam.net)
[2] Professor, Université de Lorraine, Arts et Métiers Paris Tech, CNRS, LEM3, Metz F-57000
[3] Professor, INSA-Lyon, CNRS, LaMCoS UMR5259, 69621 Villeurbanne, France
[4] Professor, Structural Mechanics and Coupled Systems Laboratory, Conservatoire National des Arts et Métiers, 75003 Paris, France

ABSTRACT

The seismic behavior of bridge cranes is an important safety issue for nuclear plants. An efficient time-history dynamic analysis is necessary to study the earthquake response of bridge cranes, in order to take into account the non-linear effects, such as the multi-contacts/impacts during the wheel-rail interaction. Here, three-dimensional non-linear seismic analysis is carried out in MATLAB using heterogeneous asynchronous time integrator for frictional contact/impact problems. With the proposed hybrid non-linear simulation technique, the computational time of three-dimensional numerical simulations is considerably reduced and it becomes possible to carry out three-dimensional detailed simulation of bridge cranes under earthquake with a reasonable computational time and an adequate modelling of the impacts and frictional contacts. Two different methods to impose the seismic solicitations have been also investigated. The numerical results obtained by the hybrid approach are validated in comparison with the full-explicit simulation, highlighting the accuracy and computational efficiency of the hybrid approach.

1.INTRODUCTION

The seismic behavior of bridge cranes is a very important safety issue for in nuclear power plants (NPPs), because they are widely applied in nuclear plants as handling devices for refuelling, maintenance and installation of heavy equipment. The bridge crane's failure has been also identified as a significant contributor in the probability of core meltdown in the context of seismic Level 1 Probabilistic Safety Assessment (PSA) studies performed on nuclear power plants (Richard et al. 2022). Under earthquake, the bridge crane is subjected to multi-contacts/impacts during the wheel-rail interaction. In order to take into account such non-linear effects, an efficient time-history dynamic analysis is necessary. However, in the literature, only some simplified numerical models in this field have been employed due to the important computation time of three-dimensional numerical simulations (Feau et al. 2015). Here, three-dimensional explicit/implicit multi-time step simulations are carried out in the framework of Heterogeneous Asynchronous Time Integrator (HATI) for non-smooth transient dynamics. With the proposed hybrid non-linear simulation technique, the computational time of three-dimensional numerical simulations is considerably reduced and it becomes possible to carry out three-dimensional detailed simulation of bridge cranes under earthquake with a reasonable computational time and an adequate modelling of the impacts and frictional contacts. As shown in Fig.1, an explicit time integrator for frictional contacts/impacts based on the velocity-impulse formulation (Fekak et al. 2017, Di Stasio et al. 2021) is only applied in the contact areas with a fine time scale satisfying the stability condition (Hughes 1987) to treat the non-linear wheel-rail interaction, while an implicit time integrator is adopted in the other parts with a large time step to reduce the computational time. The coupled multi-time step explicit/implicit problem is treated by a dual coupling approach providing a full versatility in terms of time integrators and time step sizes according to the partitions (Brun et al. 2015, Gravouil et al. 2015). Two different methods to impose the seismic solicitations have been also investigated. The numerical results obtained by the hybrid approach are validated in comparison with the full-explicit calculation, highlighting the accuracy and computational efficiency of the hybrid approach.

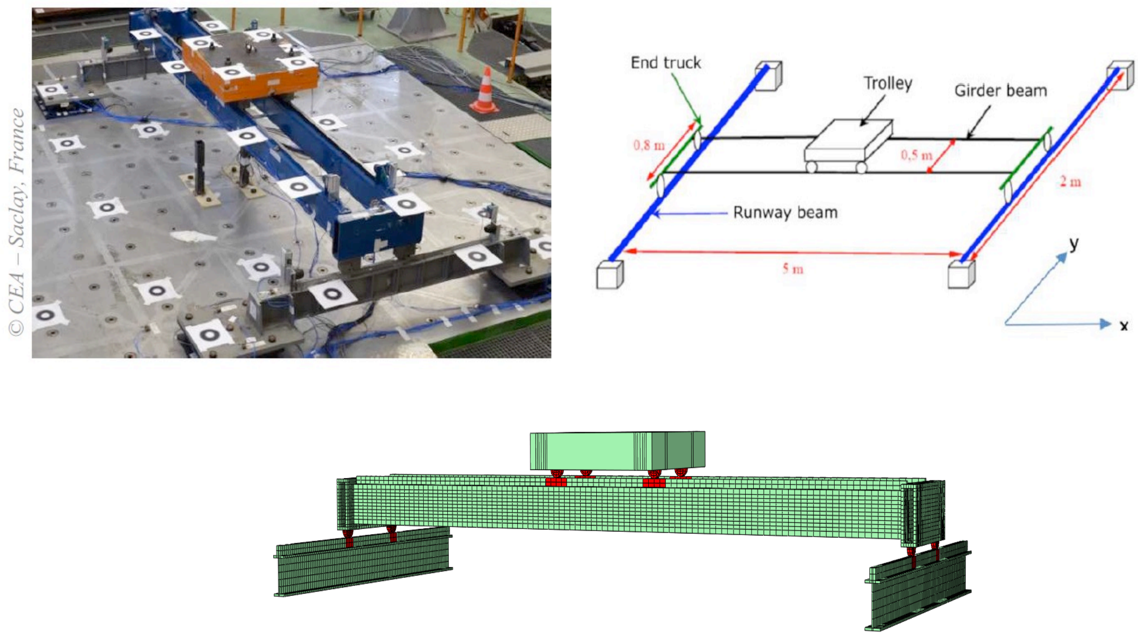


Figure 1. Numerical model of 1/5 scale mock-up of an overhead bridge crane divided into explicit subdomain (red) and implicit subdomain (green)

2. MULTI-TIME STEP EXPLICIT/IMPLICIT COUPLING APPROACH WITH FRICTIONAL CONTACTS/IMPACTS

In order to study the non-linear seismic behavior of bridge cranes, the implementation of the multi-time step explicit/implicit approach with frictional contacts/impacts in MATLAB is briefly presented in this section. The explicit event-capturing time integrator using Central Difference (CD) scheme is presented to treat the frictional contact/impact problems experienced by bridge cranes under earthquake, called CD-Lagrange scheme, which need no additional numerical parameters in comparison with the penalty method Then, the heterogeneous asynchronous coupling method (Brun et al. 2015, Gravouil et al. 2015) is employed to couple the explicit time integrator with the classical Newmark implicit time integration, in which a large time step can be adopted to reduce the computational time.

2.1 Explicit time integrator for frictional contact/impact problems

After the classical finite element discretization and the time discretization using Central Difference scheme, the semi-discrete non-smooth dynamic equation of a frictional contact/impact problem, based on the velocity-impulse formulation, can be written as below:

$$M\dot{U}_{n+\frac{3}{2}} = M\dot{U}_{n+\frac{1}{2}} + \Delta t\left(F_{ext,n+1} - C\dot{U}_{n+\frac{1}{2}} - KU_{n+1}\right) + I_{n+1} \tag{1}$$

$$I_{n+1} = \left(L_{V,n+1}\right)^T \lambda_{V,n+\frac{3}{2}} + \left(L_{L,n+1}\right)^T \lambda_{L,n+\frac{3}{2}} + \left(L_{T,n+1}\right)^T \lambda_{T,n+\frac{3}{2}} \tag{2}$$

Here, the impulse term I_{n+1} concerning all the degrees of freedom at the interface potentially in contact is represented by three Lagrange multiplier vectors to ensure frictional contact/impact conditions including the vertical contact/impact, the lateral contact/impact and the tangential friction between wheels and rails in the problem of crane bridges. $L_{V,n+1}$ is the Boolean constraint matrix to identify the degrees of freedom for the vertical contact, $L_{L,n+1}$ is to select the degrees of freedom in the lateral contact, and $L_{T,n+1}$ is for the degrees of freedom involved in the tangential friction. The velocity can be decomposed into a smooth part and three non-smooth parts $\dot{U}^V_{n+\frac{3}{2}}$, $\dot{U}^L_{n+\frac{3}{2}}$, $\dot{U}^T_{n+\frac{3}{2}}$ which can be calculated by the corresponding Lagrange multiplier in the impulse.

$$M\dot{U}^{free}_{n+\frac{3}{2}} = M\dot{U}_{n+\frac{1}{2}} + \Delta t\left(F_{ext,n+1} - C\dot{U}_{n+\frac{1}{2}} - KU_{n+1}\right) \tag{3}$$

$$M\dot{U}^V_{n+\frac{3}{2}} = \left(L_{V,n+1}\right)^T \lambda_{V,n+\frac{3}{2}} \tag{4}$$

$$M\dot{U}^L_{n+\frac{3}{2}} = \left(L_{L,n+1}\right)^T \lambda_{L,n+\frac{3}{2}} \tag{5}$$

$$M\dot{U}^T_{n+\frac{3}{2}} = \left(L_{T,n+1}\right)^T \lambda_{T,n+\frac{3}{2}} \tag{6}$$

The non-smooth transient dynamic equation Eq. (1) is completed by velocity-impulse Hertz–Signorini–Moreau (HSM) contact conditions. For example, in the case of the vertical contact/impact, the discretized kinematic constraint imposed on the contact interface is written in terms of velocity as follow: $L_{V,n+1}\dot{U}_{n+\frac{3}{2}} = 0$, which means that there is no relative movement at the contact interface. Multiplying the non-smooth equation by $L_{V,n+1}M^{-1}$, the local impact/contact equation can be obtained:

$$H_V \lambda_{V,n+\frac{3}{2}} = b_{V,n+\frac{3}{2}} \tag{7}$$

$$\begin{cases} H_V = L_{V,n+1}M^{-1}\left(L_{V,n+1}\right)^T \\ b_{V,n+\frac{3}{2}} = -L_{V,n+1}\left(\dot{U}_{n+\frac{1}{2}} + \Delta t M^{-1}\left(F_{ext,n+1} - C\dot{U}_{n+\frac{1}{2}} - KU_{n+1}\right)\right) \end{cases} \tag{8}$$

H_V is the interface operator, which is already known. The right hand-side vector $b_{V,n+\frac{3}{2}}$ only depends on the smooth velocity calculated by Eq. (3). Once derived the Lagrange multiplier vector, the non-smooth velocity associated to the vertical contact/impact can be computed. The horizontal contact/impact case or the tangential friction can be obtained in the same way. After calculating the smooth velocity and non-smooth velocity due to the frictional contact/impact, we can obtain the displacement, velocity and acceleration for the next time step.

2.2 Multi-time scale explicit/implicit subdomain coupling

The time step in Central Difference method is limited by the critical time step. Moreover, the introduction of numerical damping like Rayleigh damping could decrease further the time step. To reduce the computational time, only a small contact zone is integrated in time by CD-Lagrange algorithm. The other parts are integrated in time with classical Newmark implicit time integration associated with a larger time scale because it is unconditionally stable (Newmark 1959). The velocity continuity is ensured between the two subdomains by Lagrange multipliers on the basis of the GC coupling method. The explicit/implicit subdomain coupling problem with frictional contacts/impacts is written in the discrete form in space and time as follows:

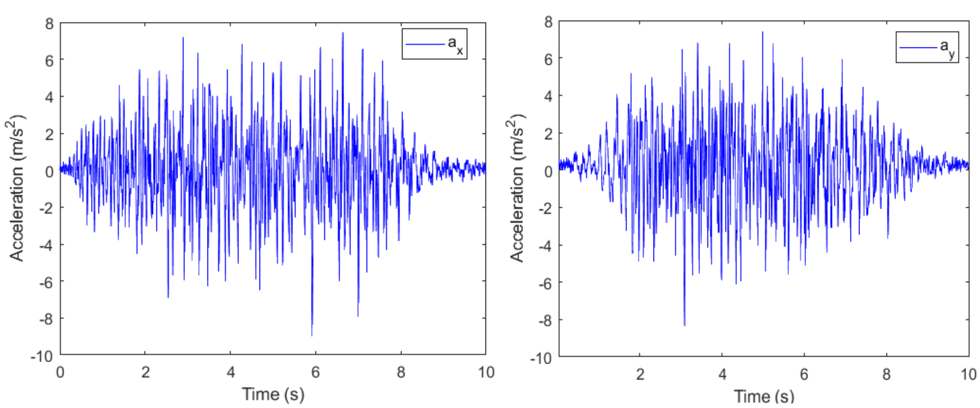
$$M_1 \ddot{U}_1^j + K_1 U_1^j = F_1^{ext,j} + F_1^{contact,j} + L_1^T \lambda^j \quad \text{for } j = 1, \dots, m \tag{9}$$

$$M_2 \ddot{U}_2^m + C_2 \dot{U}_2^m + K_2 U_2^m = F_2^{ext,m} + L_2^T \lambda^m \tag{10}$$

$$L_1 \dot{U}_1^j + L_2 \dot{U}_2^j = 0 \qquad \text{for } j = 1, \dots, m \tag{11}$$

3.NUMERICAL RESULTS

As shown in Fig.1, the numerical model is composed of trolley, girder beams, end truck beams and runway beam. Three-dimensional explicit/implicit multi-time step simulation is carried out under the seismic excitation represented in Fig.2, after the application of the gravity, with the time step ratio m between two subdomains equal to 100, which means that the time step in implicit subdomain is 100 times lager the time step in explicit subdomain. The non-linear seismic behavior, such as detachment and sliding at the contact interface, is investigated by HATI simulation, in comparison with reference results provided by full explicit simulation. In this comparison, the Rayleigh damping is not introduced in order to have a reasonable calculation time for full explicit simulation, because the introduction of Rayleigh damping leads to the important reduction of the critical time step in explicit scheme (Li et al. 2023, Belytschko et al. 2000). The friction coefficient in wheel-rail interaction is considered as 0.23. The different components of the bridge crane are assumed to be elastic. Concerning the boundary conditions, the clamped boundary conditions are applied on the bottom surface of the end of the runway beams.



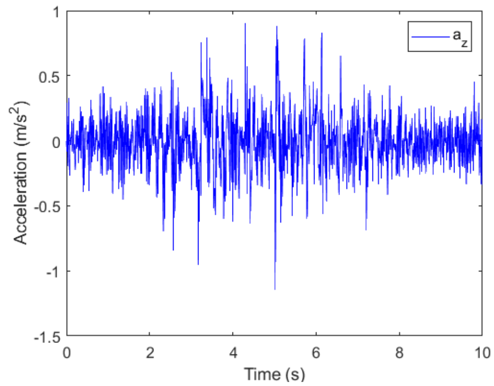
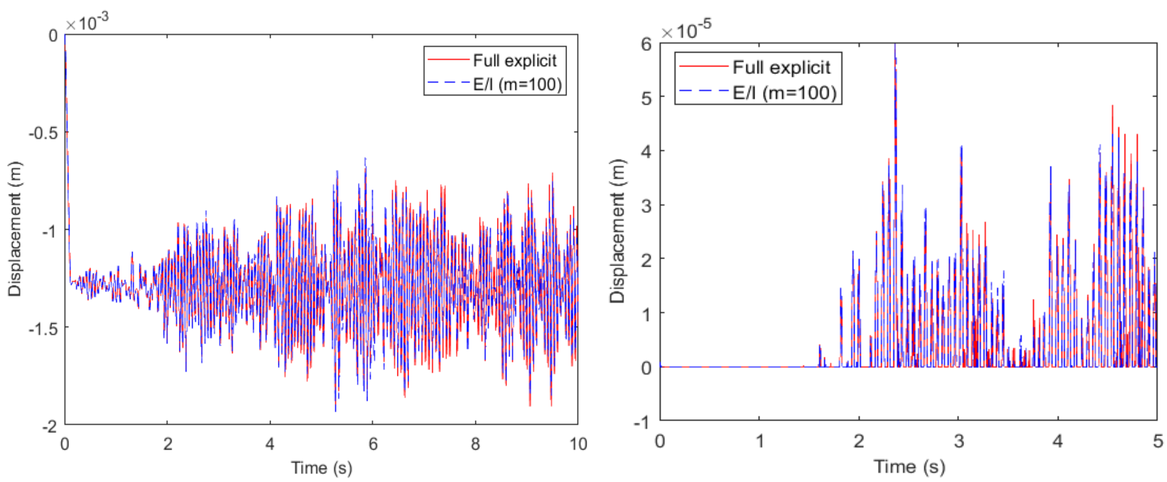


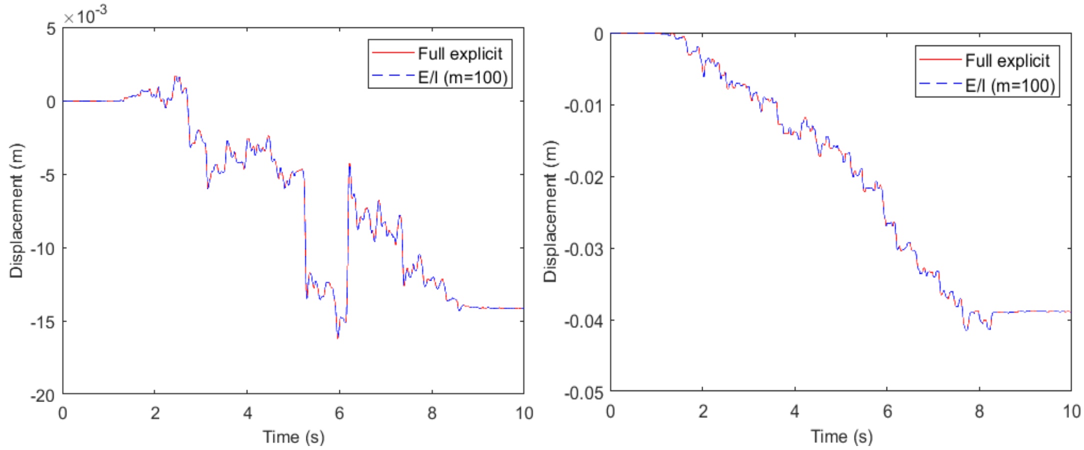
Figure 2. Three-directional seismic input in terms of acceleration

In Fig.3 (a), the vertical displacement at the center of the girder beam calculated by HATI is compared with the full explicit results. The comparison concerning the vertical relative displacement of the trolley with respect to the girder beam is plotted in Fig.3 (b). It can be seen that the results of HATI simulations achieve a very good agreement with the reference results. The detachment and recontact between the trolley and the girder beam are well reproduced by HATI simulation. Fig.4 (a) shows the sliding of the trolley on the rail of the girder beam in X direction and Fig.4 (b) provides the sliding of the end truck beam on the runway beam in Y direction. As observed, we have a satisfactory agreement between the HATI simulations and full explicit simulation.



(a) (b)

Figure 3. (a) Vertical displacement at the center of the girder beam (b) Vertical relative displacement of the trolley with respect to the girder beam



(a) (b)

Figure 4. (a) Sliding of the trolley on the girder beam along the X-axis (b) Sliding of the end truck beam on the runway beam along the Y-axis

In terms of computational time, HATI simulaiton is about six times quicker than the full explicit computation. It should be noted that, in this comparison, Rayleigh damping is not introduced. If Rayleigh damping including both mass and stiffness contributions is introduced in the full explicit simulation, with the decrease of the critical time step, the difference will be more significant (Li et al. 2023, Belytschko et al. 2000).

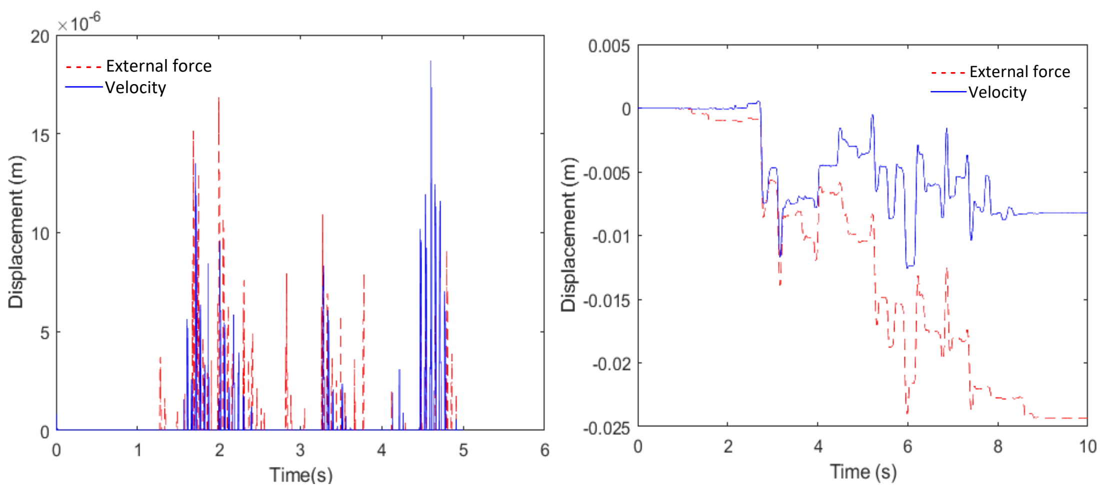


Figure 5. (a) Vertical displacement at the center of the girder beam (b) Sliding of the trolley on the girder beam along the X-axis

Finally, two methods to impose the seismic solicitations are investigated. In structural dynamics, the seismic acceleration signal is classically applied to the whole model as an external force to simulate the earthquake. In the case of bridge cranes, all the components will be subjected to the same signals. This is true when there is a rigid body without non-linear effect like detachment or sliding. However, when these non-linear effects are taken into account, the acceleration applied on each component is different. For example, in reality, the sliding of the trolley is due to the frictional force between the trolley and the girder beam. The maximum effort transmitted to the trolley is controlled by the frictional law, which means that the acceleration cannot exceed the maximum acceleration provided by the frictional force which depends on the normal contact force and the friction coefficient. In this case, the acceleration applied on the trolley may not be the same as the seismic signal. For this purpose, the acceleration signals of the earthquake are transformed into velocity signals. The three-dimensional velocity signals are applied to the boundary conditions on the runway beams via Lagrange multipliers. In this manner, the behavior of the trolley is controlled directly by the frictional contact / impact, not by the seismic acceleration signals.

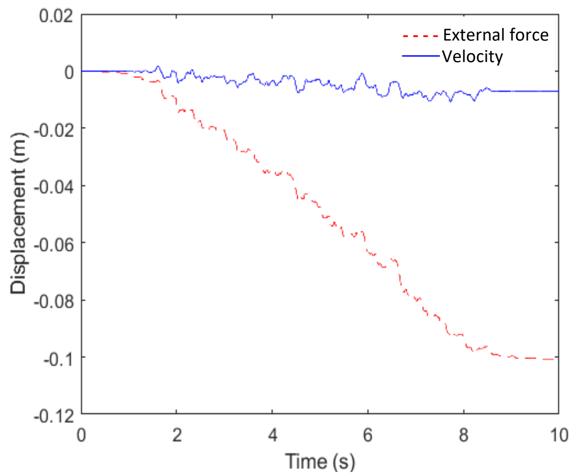


Figure 6. Sliding of the end truck beam on the runway beam along the Y-axis

The comparison between the two methods is shown in Fig.5 and Fig.6 using the hybrid approach. To better illustrate the difference between the two methods, the frictional coefficient is chosen to be 0.01. For the detachment and recontact shown in Fig.5 (a), in the case that the acceleration is applied to the whole model as an external force, even though the trolley is detached, the external force is still applied on the trolley, which is not true and could affect significantly the relative movement. Concerning the sliding in Fig.5 (a), and Fig.6, as discussed before, with the external force method, the acceleration applied on the trolley could surpass the maximum acceleration provided by the frictional force, which can explain why the sliding of the trolley is more important. On the contrary, the application of the earthquake by Lagrange multipliers reproduces better the reality and gives the freedom to apply a different acceleration for each component of the structure under seismic motion.

4. CONCLUSION

Three-dimensional detailed simulations of bridge cranes under earthquake are carried out in MATLAB with a reasonable computational time and an adequate modelling of the impacts and frictional contacts. using heterogeneous asynchronous time integrator for frictional contact/impact problems. The comparison between HATI simulation and full explicit computation gives a satisfactory agreement, illustrating the accuracy and the efficiency of the proposed hybrid approach. Two different methods to apply the seismic solicitations have been also investigated. The comparison between the two methods shows that it is preferable to apply the earthquake by Lagrange multipliers in terms of velocity on the boundary conditions to reproduce the non-linear behavior. In the future work, the influence of differential motions of the crane supports could also be analysed on the basis of the proposed numerical model.

REFERENCES

Belytschko, T., Liu, W. K. and Moran, B. (2000). *Nonlinear Finite Elements for Continua and Structures*. Wiley, New York, USA.

Brun, M., Gravouil, A. and Combescure, A. (2015). “Two FETI-based heterogeneous time step coupling methods for Newmark and α-schemes derived from the energy method,” *Computer Methods in Applied Mechanics and Engineering,* 283, 130-176.

Di Stasio, J., Dureisseix, D., Georges, G. and Gravouil, A. (2021). “An explicit time-integrator with singular mass for non-smooth dynamics,” *Computational Mechanics*, 68, 97-112.

Feau, C., Politopoulos, I., Kamaris, G. S., Mathey, C., Chaudat, T. and Nahas, G. (2015). “Experimental and numerical investigation of the earthquake response of crane bridges,” *Engineering Structures*, 84, 89-101.

Fekak, F., Gravouil, A., Brun, M. and Depale, B. (2017). “A new heterogeneous asynchronous explicit–implicit time integrator for nonsmooth dynamics,” *Computational Mechanics*, 60, 1-21.

Gravouil, A., Combescure, A. and Brun, M. (2015). “Heterogeneous asynchronous time integrators for computational structural dynamics,” *International Journal for Numerical Methods in Engineering,* 102, 202-232.

Hughes, T. J. R. (1987). *The Finite Element Method: Linear Static and Dynamic Finite Element Analysis*. Prentice-Hall, Englewood Cliffs, NJ.

Li, S., Brun, M., Gravouil, A. and Fekak, F.E. (2023). “Explicit/implicit multi-time step simulation of bridge crane under earthquake with frictional contacts and high-frequency Rayleigh damping,” *Finite Elements in Analysis and Design*, 220,103946.

Newmark, N. M. (1959). “A method of computation for structural dynamics,” *Journal of the Engineering Mechanics Division (ASCE),* 85, 67-94.

Richard, B., Robin-Boudaoud, M., Viallet, E., Cherubini, S., Berger, J. and Voldoire, F. (2022). “Overview of the research activities in earthquake engineering and seismic risk assessment within the joint framework CEA-EDF-FRAMATOME-IRSN,” *26th International Conference on Structural Mechanics in Reactor Technology* (SMiRT-26), Berlin, Germany.