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DYNAMIC BEHAVIOUR OF CRANE BRIDGES – PRESENTATION OF THE OECD/NEA INTERNATIONAL BENCHMARK 2020

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1. Abstract

Within the context of Probabilistic Safety Assessment (PSA) studies Level 1 (which deals with risk of core damage) performed on nuclear power plants, crane bridges failure have been identified as a contributor to the probability of core meltdown. Depending on the reactor type and on the period of design, one of the significant failure mode may 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.

In this context, it is necessary to improve knowledge about the dynamic behaviour of this equipment in order to fully understand how failure would occur in the case of far beyond design loadings induced by the most severe earthquakes (that are considered in risk assessment). In this view, it appears to be important to estimate accurately the forces transmitted to the anchorages. In addition, the incorporation of diverse sources of uncertainties through a fragility curve still raises several questions such as: what are the main variables to be considered as random? What are the failure criteria to be used? Does the hypothesis of a lognormal distribution remain justified for seismic inputs whose intensity is beyond the design range?

In order to provide answers to these questions, a benchmark endorsed by the Working Group on Integrity and Ageing of Components and Structures (WGIAGE) of OECD/NEA/CSNI started in 2020. The main objectives of this action are (i) to identify best practices to model seismic behaviour of crane bridges; (ii) to identify relevant failure criteria; and (iii) to establish international consensus on the definition of seismic fragilities of cranes.

An experimental campaign on a scaled model of an overhead crane bridge was carried out in 2015 on the AZALEE shaking table of CEA in France and the results have been gathered in a large database. On one hand, some of these data will be used by participants to characterize and calibrate their numerical models and, on the other hand, some other data will be used to assess the predictive capacity of the models. The benchmark will be concluded by a restitution workshop where the different participants will gather to exchange and discuss their models and results. In this way, best practices for modelling overhead cranes under seismic load will be identified. The workshop will provide a synthesis of lessons learnt and recommendations based on findings of the benchmark analysis. A proceeding report including documents submitted by participants may be published and the findings of the benchmark analysis will be summarized in the restitution workshop to be held in 2021 and a NEA report in 2022.

In this paper, an overview of the benchmark will be presented, including main objectives, test specimen, and detailed benchmark process.

Keywords: Overhead Crane Bridge; benchmark; dynamic behaviour; nuclear component

2. Introduction

Crane bridges are handling devices used to lift and transfer heavy loads, widely used in the industry, including the nuclear industry. Assessing the dynamic behaviour of crane bridges may constitute an important issue for nuclear safety in order to prevent the risk of collapse or impact onto important component for safety. In addition, modelling and predicting the mechanical behaviour of such a device is a motivating scientific challenge. Within the context of seismic Level 1 Probabilistic Safety Assessment (PSA) studies, these devices have been identified as significant contributors to the probability of core meltdown. Indeed, a major problem may occur if part of the crane or all falls on sensitive structures or component. That is why, in addition to devices installed on crane bridges to prevent various parts from falling down, improving the modelling of the seismic behaviour of such an equipment may also be useful. Nevertheless, this modelling is particularly challenging due to the complexity of cranes and due to the importance of contact and sliding, as well as dissipation, in determining their dynamic response. The behaviour of the anchoring seems to be the primary cause of failure of this equipment. Consequently, it is necessary to enhance the knowledge of this equipment in order to fully understand its behaviour when subjected to earthquakes and, in particular, to assess the efforts transmitted to the anchorages.

In this context, the main objectives of this action are to identify best modelling practices regarding the crane bridges and to identify relevant failure criteria. To achieve these objectives, IRSN has initiated a benchmark under the aegis of the OECD/NEA. IRSN will also provide the data to be used within the framework of the benchmark, taken from an extensive experimental program performed on a reduced-scale crane bridge mock-up.

This experimental campaign on a scaled model of an overhead crane bridge was carried out in 2015 on the AZALEE shaking table of CEA in France and has produced a large database. Some of these data will be used by participants to characterize and calibrate their numerical models and, subsequently, the other data will be used to assess the predictive capacity of the models in case of high intensity earthquakes. In this way, best practices for modelling crane bridges under seismic load will be identified and attempts to make international consensus emerge may be possible.

A specific attention is paid to the characterization of the numerical models developed by the participants. Furthermore, additional data are provided to ensure an efficient control of the boundary conditions. The benchmark will be concluded by a restitution workshop where the different participants will be gathered to exchange and discuss their models and results they have obtained. The workshop will provide a synthesis of lessons learnt and recommendations based on findings of the benchmark analysis. A proceeding report including documents submitted by participants may be published and the findings of the benchmark analysis will be summarized in a NEA report.

In this paper, the state of the art on experimental tests carried out to study the dynamic behaviour of overhead cranes is first addressed in section 3. Then, in section 4, a general description of the specimen is provided. The different experimental tests are presented in section 5. A general presentation of the different phases of the benchmark is made in section 6. In section 7, the main modelling lines to be considered during the modelling exercise are recalled. Finally, in section 8, the objectives are recalled and conclusions are drawn.

3. State of the art

The scientific literature, dealing with the issue of the crane bridge seismic behaviour, is not very extensive; only a few studies are reported. [1] conducted tests of a 1/10 scaled crane bridge model to study the sliding of the wheels on the rails under horizontal seismic excitation whereas [2] performed seismic tests on a 1/8 scaled crane bridge model to study the behaviour in the vertical direction, i.e. the rebound and impacts of the entire crane bridge on the rails of the rolling structure. They were able to show that the reaction forces at the wheels can be predicted by a linear analysis.

In [3], the authors studied the seismic behaviour of a polar crane bridge using a comprehensive finite element model. It has been recognized, from sensitivity studies, that friction between the wheels and the rail has a significant influence on the seismic response of the crane. Indeed, a proper consideration of the friction between the wheels and the rails reduces the seismic response intensity of the crane by 4 to 6 times. [4] discussed about simplified approaches that take into account the reduction of crane bridge forces due to sliding such as considering a reduced spectral response taking into account the sliding effect. [5] analysed the behaviour of a simplified scale model of a crane bridge subjected to random unidirectional excitations and compared it with experimental tests. The numerical model of the scaled model was in good agreement with the experimental evidence. [6] conducted a shaking table experimental campaign on a model of a crane bridge focusing on the uplift response of the trolley. The authors showed that the horizontal excitation can cause a displacement jump at the trolley wheel due to the rocking behaviour. On the other hand, vertical excitation can reduce sliding of the girder beams.

To have a further insight into the earthquake response of crane bridges, a first experimental campaign on a 1/5 scaled model was carried out in 2010 by IRSN on the AZALEE shaking table of the French Sustainable Energies and Atomic Energy Commission (CEA) in Saclay [7]. The seismic tests were carried out for different configurations (trolley location, braked and rolling wheels) under several excitations signals (bi-axial, tri-axial, growing PGA values). The objective was to study the ability to reproduce numerically the highly non-linear behaviour of the crane bridge. However, since the fall of part or all of the crane bridge represents a major safety issue, it is also important to investigate the anchoring behaviour. For this purpose, another experimental campaign [8] was conducted in 2015 on the AZALEE shaking table with the same mock-up as the one used in 2010 in order to determinate accurately the reaction forces on the runway beams. Henceforth, the crane supports have been equipped with suitably designed load cells to measure the reaction forces on the runway beams [8], [9]. The present paper refers to this last experimental campaign.

4. General description of the specimen

The mock-up is a simplified 1/5 scaled model of a 22.5 m long overhead crane bridge. Its dimensions have been derived from the dimensions of an real crane bridge at the Phenix research reactor [7]. Given the fact that the shaking table is a 6 m x 6 m table, this scale is the largest one that could be considered. The bridge steel girders that support the crane trolley have a rectangular hollow cross-section of 1050 mm x 2100 mm. The width of the flanges cross-section and vertical walls are 21 mm and 12 mm respectively. The runway beams are continuous I type steel beams with a typical span of 10 m. The height of the section is 1500 mm, the flanges width and thickness are 600 mm and 35 mm respectively and the web thickness is 12 mm. One important issue for the design of the model was the determination of the similarity law which is presented in [7]. In the following, a brief description paragraph is devoted to each component of the mock-up.

The crane bridge mock-up is composed of several components, as shown in Figure 2: a trolley, two rails, wheels, girder beams, end truck beams, runway beams, and load cell blocks which are included between the shaking table upper plate and the crane bridge mock-up.

The crane instrumentation includes accelerometric measurements at different points on the mock-up, local displacements of the beams and six-axis force cells for force measurement.

Several configurations of the entire crane bridge are considered. There are 3 factors which determine the nature of the mock-up configuration: the initial position, the different wheel conditions and the general state.

1. *Initial positions*: the initial position of the trolley on the girder beams and the initial position of the end trucks on the runway beams:
    a. *Centered initial position*: it consisted in positioning the girder beams and the trolley in the middle of the length of the rails that support them.

   b. *Decentered initial position*: it consisted in positioning the girder beams and the trolley at a quarter of the length of the rails supporting them.

2. *Different wheel conditions* (roller or fixed):
   a. *Fixed wheels*: all wheels are fixed. They can only move by frictional sliding.
   b. *Mixed wheels*: half of the wheels are rollers and the other half is fixed.
3. *General state:*
   a. *Blocked state:* it consists in making the system linear by immobilizing all the moving elements in all directions, each element being centered on its rail track. The girder beams were therefore connected to the runway beams laterally by clamps and vertically by clamps. The trolley was connected to the girder beams by lateral clamps.
   b. *Free state:* no blocking conditions are applied on the moving components of the mock-up.

Initial positions		Different wheel conditions		General state	
Centered	Decentered	Fixed wheels	Mixed wheels	Blocked state	Free state

Table 1: Summary of the configurations.

The different test configurations are summarized in Table 1. Figure 1 shows two different configurations: centered and not decentered initial positions.

Figure 1: Two tested configurations. The first one (left) is centered and the second one (right) is not centered.

5. Test campaign

The test campaign was carried out in several phases, including modal identification of the mock-up and of each component and seismic tests in different mock-up configurations. Hammer shocks and white noise tests were performed for initial modal characterization of the crane bridge mock-up and its components. Impulsion tests were conducted for friction characterization. Bi-axial and tri-axial seismic tests were conducted to study the dynamic behaviour of the crane bridge mock-up. Finally, post-seismic hammer shock tests were performed for final modal characterization. The 2 summarizes the various experimental tests carried out.

Experimental tests	**Component**	**Avalable data**
Hammer tests	Modal identification of the load cell block	Measured displacements Measured accelerations Measured forces
	Modal identification of the runway beam	
	Modal identification of the girder beam	
	Modal identification of the mock up	
White noise tests	Complete crane	
Impact tests	Characterization of friction between moving parts	
Seismic tests (bi-axial and tri-axial)	Complete crane (0.25g to 2.0g)	

Table 2: The available experimental tests.

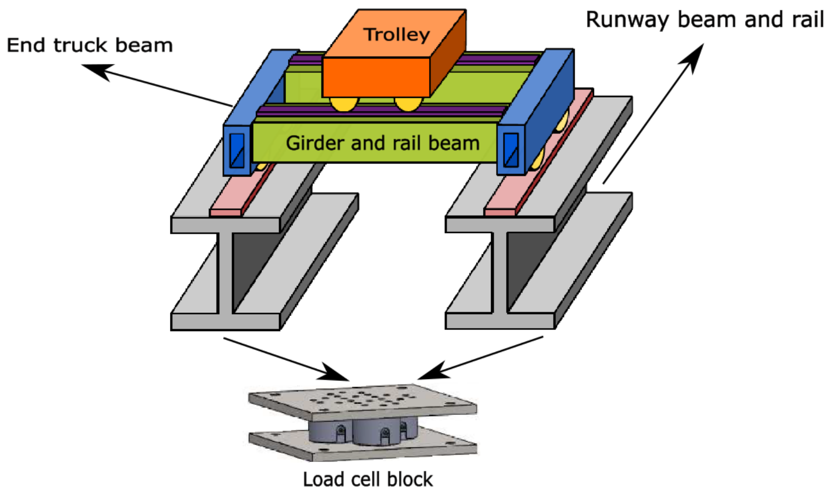

Figure 2: Crane components.

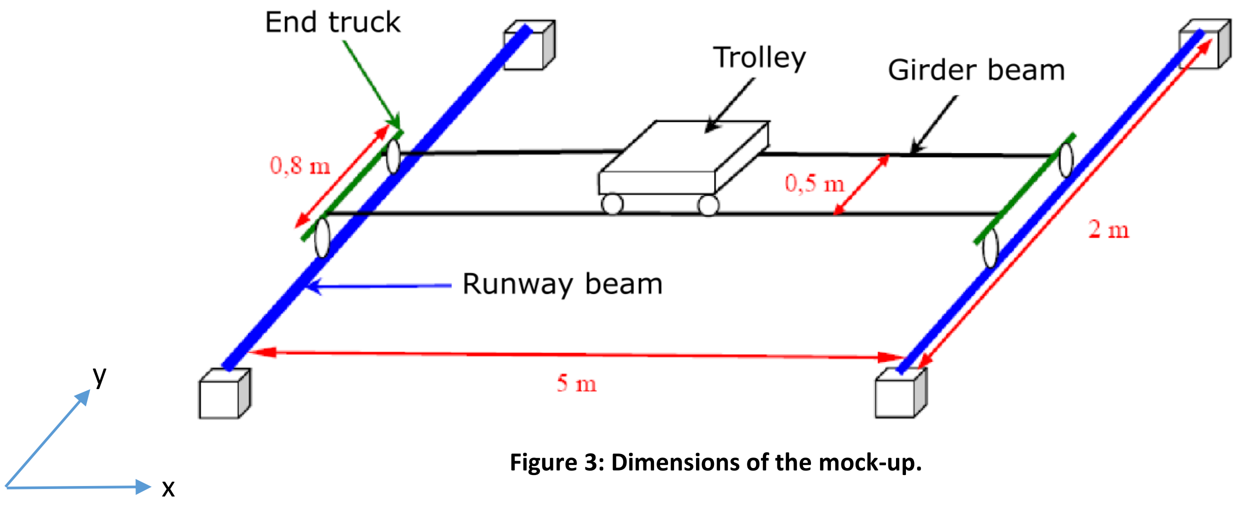

Figure 3: Dimensions of the mock-up.

6. General presentation of the Benchmark

The international benchmark is organized in three main tasks which are described thereafter:

I. OECD/NEA benchmark phase 1: Announcement and participant registration
   1. First announcement of the benchmark and declaration of intention from potential participants.
   2. Definition of the program, rules and schedule of the benchmark.
   3. Official registration of participants.
   4. Description of the participants' modelling assumptions.

II. OECD/NEA benchmark phase 2: Characterization and calibration of the proposed models
   1. Necessary data are provided to participants: detailed descriptions of the geometry of the mock-up and all its components. Similarly, for boundary conditions.
   2. Calibration for low seismic intensities is envisaged. Participants will be provided with experimental data to calibrate their models.
   3. Calibration for significant seismic intensities is envisaged. Participants will be provided with experimental data to calibrate their models.

III. OECD/NEA benchmark phase 3: Assessment of the predictive capabilities of the modelling approaches
   1. Blind non-linear simulations to assess the predictive capabilities of the models.

IV. OECD/NEA international restitution workshop

The benchmark will be concluded by a restitution workshop where the different participants will be gathered to exchange and to discuss about their assessment methods and results. In this way, best modelling practices will be identified. The workshop will provide a synthesis of lessons learnt and recommendations based on the previous task results. Figure 4 summarizes the main phases of the Benchmark.

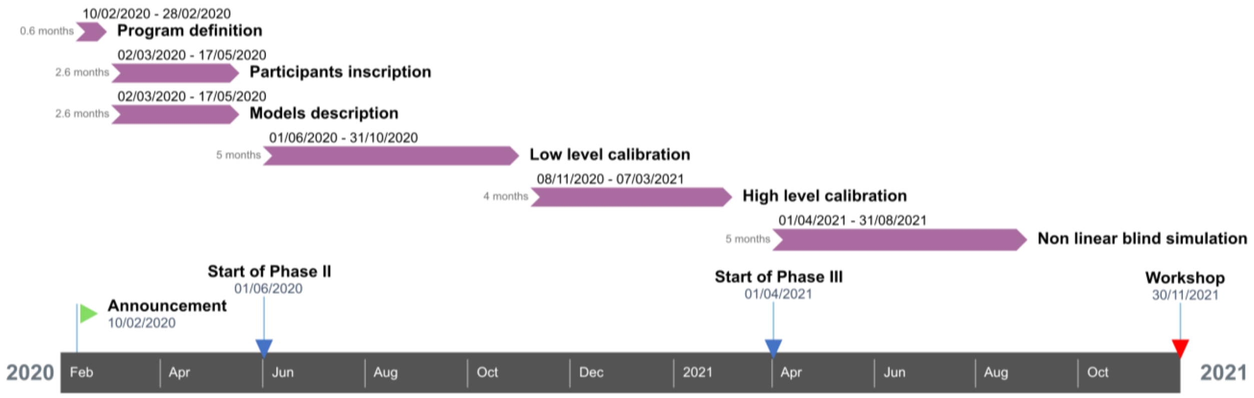

Figure 4: Benchmark timeline.

Phase I deals with the development and on the characterization of the numerical models. General information about the numerical model developed as well as specific information about the way to describe contacts and local shocks will be required.

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 that represents the mock-up geometry;
2. the definition of the interfaces between the different components of the mock-up;
3. the definition of the boundary conditions.

General information regarding the aforementioned items is required. The possibility to update these data according to the phase of the benchmark is allowed. However, the data will be gathered and analyzed at the end of each phase.

7. Numerical modelling guidelines

In this section, we highlight the main items to be considered during the modelling works that should be carried out by the participants in the Benchmark.

7.1 Modal identification

To develop a reliable numerical model, a modal identification of the different components as well as of the full mock-up is necessary. The comparison between the experimental and the numerically computed eigenfrequencies and modeshapes must be carried out. Parameters of the numerical model need to be calibrated on the basis of the experimental results. For this purpose, low and high intensity seismic tests are used.

7.2 Connections modelling between the different components

A particular attention must be paid to how the connecting elements between the different components (i.e. the connections between the wheels and their supports) are modelled in order to avoid the risk of over or under-evaluation of the equipment response. Two important connections should be reliably considered:

i. between the trolley and the girder beams;

ii. between the end trucks and the runway beams.

7.3 Non-linear phenomena modelling

During an earthquake, the crane bridge is exposed to various non-linear phenomena. The main causes of these phenomena are:

1. friction and slip between moving parts;
2. multiple local shocks between the wheels and the rails;
3. bridge locking.

The adequate modelling of non-linearities at the contact level is a crucial point of the benchmark. These non-linear phenomena are described hereafter.

7.4 Friction and sliding

A bi-axial sliding is likely to occur a first longitudinal sliding of the fixed rollers on the rails and a second lateral sliding between the cheek of the rollers and the side of the rail.

Since the modelling of an anisotropic sliding may sometimes be complex, an isotopic behaviour could therefore be used [8]. For wheels that can roll, only lateral sliding can be considered. On the other hand, for fixed wheels, only the longitudinal sliding can be taken into account.

7.5 Local shocks

During an earthquake, the crane bridge is subjected to multiple shocks between the wheels and the rails, which cause non-linear energy dissipation modes that are complex to model. These shocks can be described by different ways: (i) non-linear contacts (implicit); (ii) explicit contacts, solved, for example, by penalty-like methods [7]; (iii) or also by multi-scale approaches as proposed in [9] such that a numerical coupling between the implicit and explicit schemas are performed with a heterogeneous asynchronous time integrator [9].

7.6 Bridge locking

For high level seismic tests (PGA equal to 2.5g), a phenomenon of bridge locking caused by the inclination of the girder beams between the runway beams has occurred. This phenomenon results from the movement of the two end truck beams in two opposite directions. In addition, in the case the two end truck beams move in the same direction but with a large gap, bridge locking may also occur. Since this phenomenon appears for high seismic load levels (PGA around 2.5g), therefore, it is not necessary to take it into account in the modelling when seismic loads are less than 2g.

8. Conclusion

Within the framework of probabilistic safety assessments (PSAs), there is a need to study in more detail the behaviour of overhead cranes with regard to seismic risk. To this end, a major experimental campaign was initiated by IRSN on the CEA's AZALEE shaking table in Saclay, France. Tests were performed in different configurations using a small-scale mock-up. This experimental campaign provided a wide range of results that could be used to improve knowledge of the modelling of this type of equipment. To this end, IRSN has initiated a benchmark under the aegis of the OECD/NEA. In this paper, we have presented an overview of this international benchmark based on the experimental results. The experimental campaign, as well as the mock-up, were described. The different phases of the benchmark were presented as well as the main lines of modelling to be considered. The benchmark will be concluded by a restitution workshop where the different participants will be gathered to exchange and to discuss their models and results. In this way, best modelling practices may be identified. The workshop will provide a synthesis of lessons learned and recommendations, based on the previous task results, which will be published in an OECD/NEA report.

9. References

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