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COMPARATIVE SEISMIC ANALYSIS OF OVERHEAD CRANE ON STEEL FRAME CARRYING STRUCTURE: EVALUATION OF ADEQUATE EQUIPMENT-STRUCTURE INTERACTION MODELING

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ABSTRACT

Overhead travelling cranes are common equipment in industrial facilities and are usually designed to resist dead and live loads. Seismic motion produces noteworthy horizontal loads that can cause damage and jeopardize the stability of the crane or its components. Moreover, effects of seismic loads on the crane depend strongly on the mechanical characteristics of the carrying structure. In some cases, travelling cranes may represent an important mass with respect to the carrying structure and their support arrangement may constitute a real constraint for the dynamic response of the carrying structure. For steel frame carrying structures, due to their flexibility and light mass, dynamic interaction with massive travelling cranes (especially for crane multi-support configurations) can significantly influence seismic response. Adopting a proper seismic analysis technique is in such cases an essential step for the seismic design of overhead cranes since it should describe accurately the dynamic response of the crane on carrying structure.

Three numerical analysis techniques are examined in the present study: (a) uncoupled response spectrum method; (b) inertial coupled response spectrum method; (c) dynamic coupled response spectrum method. The aim of the study is to evaluate conservatisms and inadequacies associated to each technique. The study concerns the seismic response of an overhead crane supported by a steel frame building exhibiting linear elastic material behaviour and modelled using a three-dimensional finite element mesh. In order to cover a wide range of configurations, different crane and trolley locations and crane loading states are taken into account in the study.

Since structural integrity and stability assessment of travelling crane under seismic loads is the final objective of the study, conservatisms and/or inadequacies of each analysis technique are accounted for with respect to structural failure and standard collapse criteria.

The implementation of a suitable analysis technique may lead to a radical redefinition of seismic capacity and stability margins of travelling cranes. The present paper outlines the key features of crane and carrying structure that must be accounted for in order to carry out a concise seismic analysis.

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INTRODUCTION

Analysis of crane seismic response must represent adequately crane and carrying structure features, as well as crane-carrying structure interaction when it has a significant influence in response. Nevertheless, detailed analyses, such as time history on integrated model, often involve high time-machine cost and may not lead to a great improvement in results. On this matter, modal-spectral method can be an interesting approach to reduce time-machine resources. However, simplification requires a preliminary examination of the system dynamic behaviour.

Inertial, kinematic or dynamic crane-carrying structure interaction may influence seismic response, particularly when crane represents an important mass relatively to the carrying structure. Modal features of crane and carrying structure as well as support arrangement of crane point out the potential influence of interaction.

This paper presents a comparative seismic analysis of overhead crane on steel frame carrying structure in which the influence of inertial and dynamic interaction phenomena is evaluated.

METHODOLOGY

Seismic response of overhead crane is calculated by a modal-spectral analysis, taking into account up to six configurations (varying the location of overhead crane and trolley as well as the loading state and height of travelling hoist), as shown in Fig.1.

Three seismic analysis techniques are implemented in order to carry out a comparative analysis of results. The main differences between three methods are the seismic load representation and the modelling of the structures.

Uncoupled response spectrum method (a) is carried out with a model of overhead crane apart. Seismic load is represented by floor spectra at support level of overhead crane neglecting any interaction effect between crane and carrying structure. Floor spectra represent the carrying structure response at support points of overhead crane.

Inertial coupled response spectrum method (b) deals with a modal-spectral analysis on overhead crane model introducing floor spectra at support level as the input seismic load. Floor spectra are calculated from modal features of steel frame carrying structure introducing overhead crane as lumped masses on rails to take account of inertial crane-carrying structure interaction. Obeying to standard engineering practice, lumped masses are equally distributed on both tracks, with no regard to the real distribution of mass that depends on bearing conditions and position of trolley. Lumped masses representing crane are coherent with travelling hoist loading state for each configuration.

Dynamic coupled spectrum analysis (c) takes account of inertial and kinematic interaction, using a complete model of the crane attached on the steel frame carrying structure, in order to evaluate the influence of multi-support arrangement of crane.

Floor spectra calculation

Floor spectra calculations are carried out with code FSG (Igutsa and Der Kiureghian, 1995) using soil response spectrum and modal parameters from steel frame carrying structure, such as modal frequencies, modal masses and mode displacements at support points of overhead crane.

Floor response spectra for each direction of the seismic motion are combined by SRSS (square root of the sums of squares) rule in order to obtain the response spectra of the combined three-dimensional seismic excitation.

Floor spectrum introduced in crane seismic analysis is the envelope of floor response spectra obtained for the six configurations of overhead crane and trolley. Floor spectra for each configuration correspond to carrying structure seismic response at different sets of attachment points.

Modelling and material properties uncertainties for the seismic calculations are introduced in floor response spectra by the broadening of the spectrum around frequencies of peak response on a range of $\pm 15\% f_{peak}$. Final floor response spectrum implemented in analysis is the broadened envelope of floor spectra for all configurations.

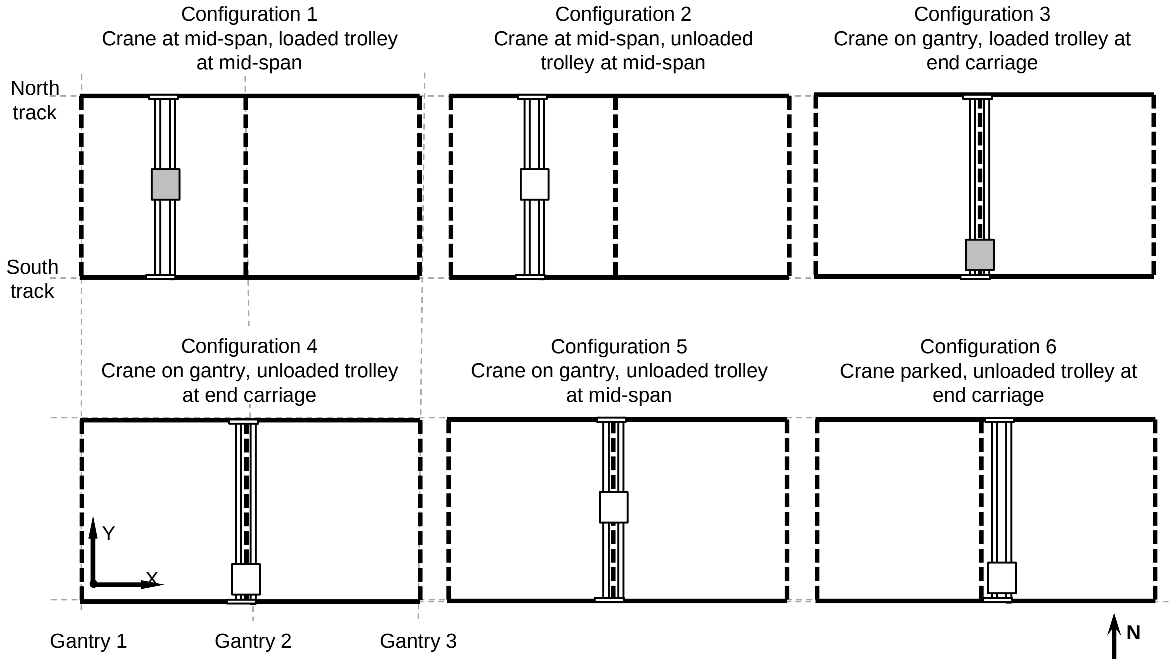

Figure 1. Overhead crane configurations

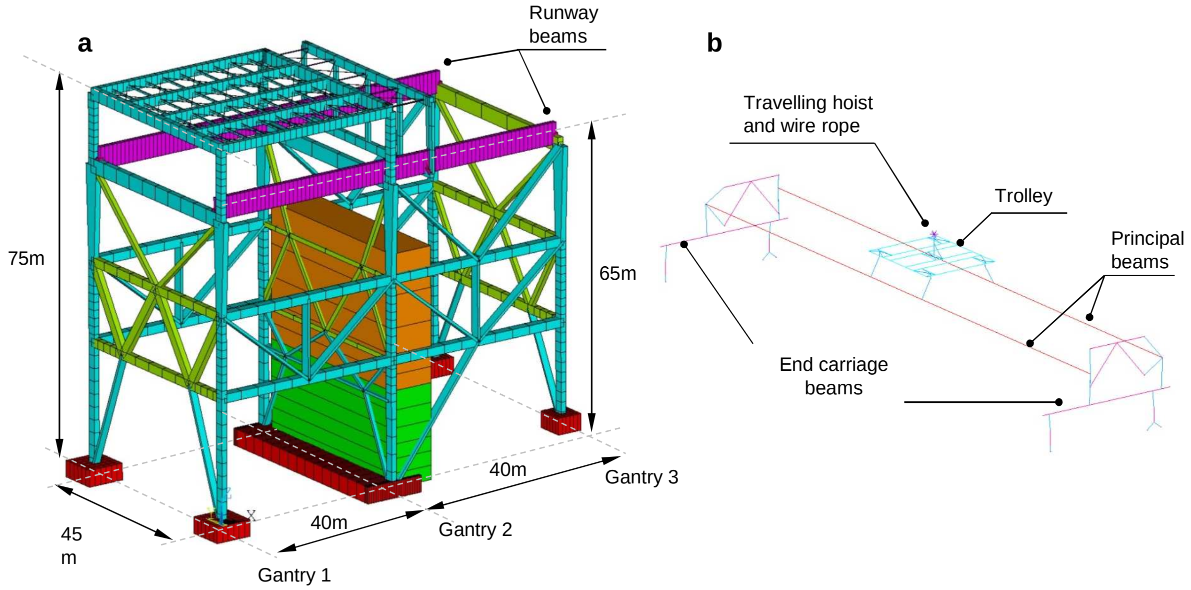

Figure 2. Numerical model : a) steel frame carrying structure, b) overhead crane

Table 1. Mass of crane and carrying frame structure

Configuration		Unloaded trolley		Loaded trolley	
Element		*m*	%	*m*	%
		[t]	[-]	[t]	[-]
Overhead crane	Principal beams	95.0	4.7%	95.0	4.5%
	End carriage beams	16.6	0.8%	16.6	0.8%
	Electrical and mecanical components	9.4	0.5%	9.4	0.4%
	Trolley and travelling hoist	31.7	1.6%	106.7	5.1%
Carrying steel frame structure	Runway beams	199.1	9.8%	199.1	9.4%
	Steel frame	1685.7	82.7%	1685.7	79.8%

Mass of crane and trolley :	152.7	7%	227.7	11%
Mass of carrying frame structure :	1884.7	93%	1884.7	89%
Total mass :	2037.4	100%	2112.4	100%

Modal analysis

Modal analysis of overhead crane and steel frame carrying structure is carried out in order to identify representative dynamic response of each structure. Illustrative crane eigenmodes represent more than 1.6% of the total mass of overhead crane with unloaded trolley, or 2.4t. In the aim to apply an equivalent filter criterion, representative eigenmodes for steel frame carrying structure are those involving more than 0.13% of the total mass of steel frame carrying structure.

Mass of overhead crane and trolley components and carrying structure are given in Tab. 1 and fundamental eigenfrequencies are given in Fig. 3.

Spectrum analysis

Maximum seismic response in each direction is obtained by implementing a complete quadratic combination (CQC) of principal eigenmodes of the studied structure, overhead crane apart (a, b) or crane on carrying structure (c). Newmark combinations of spectrum response, according to ASN/GUIDE/2/01 (2006) and given in Eq.(1), are implemented to take account of the effect of three directions of seismic excitation (*SX*, *SY*, *SZ*).

$$\begin{aligned} &\pm SX \pm 0.4SY \pm 0.4SZ \\ &\pm 0.4SX \pm SY \pm 0.4SZ \\ &\pm 0.4SX \pm 0.4SY \pm SZ \end{aligned} \tag{1}$$

NUMERICAL MODEL

A three dimensional model of crane and steel frame carrying structure has been developed in ANSYS (ANSYS, 2007). Both structures are represented by 3D beam elements, with linear visco-elastic material definition. Numerical models of steel frame carrying structure and overhead crane appear in Fig. 2.

Steel frame carrying structure

Steel frame carrying structure is composed of three gantries, orientated along N-S vertical planes, separated of 40m each. Each gantry is 75m high and 45m large. Horizontal and diagonal metallic beams are located in the plane of gantries for the transmission of horizontal loads.

Travelling runway beams are I-shaped metallic beams located at 65m height from the basis of the steel frame carrying structure. North and South crane long travel tracks are located on top of I-shaped runway beams and extend between two gantries, along 40m. Runway beams are continuous beams simply supported on gantries, with two spans of 42m.

Overhead crane

Overhead crane extends across 42m and lies on two rails. Long travel rails, parallel to E-W direction, are connected on top of the I-shaped runway beams. Two box girder metallic beams constitute the principal beams of crane. Trolley runway, parallel to N-S direction, is located on top of these beams. Principal beams are supported on two box girder end carriage beams, located on North and South track. Each end carriage contains a motor wheel and two free wheels (as shown on Fig. 4).

The main structure of crane is modelled by 6 degree of freedom 3D-beam elements. Beams are represented at the cross section gravity centre fibre and connexion between beams is assured by rigid link elements. The trolley is represented by rigid beams of equivalent mass that are linked to principal beams. Travelling hoist and wire rope are modelled as a spring-mass system with equivalent frequency of oscillation. The length of the wire rope is therefore taken into account in the modal analysis.

Crane bearing conditions

Bearing conditions of overhead crane represent the link between crane and rails. These conditions introduce some simplifications inherent to a linear approach since sliding or uplift, as a non-linear phenomena, cannot be reproduced. Likewise, the complex link of crane on cross travel direction, with a gap between doubled flanged wheels and rail (clearance) may result in a non-linear pounding response that cannot be captured with a linear analysis.

Concerning long travel direction, motor wheels are rigidly linked to rails while free wheels are allowed to slide. On cross travel direction, it is considered that only North wheels assure the stability of the crane, while South wheels are free. In vertical direction, all wheels are rigidly linked to their rails. All wheels are considered as an articulated link.

MODAL ANALYSIS

Overhead crane eigenmodes

Crane fundamental modal shapes are bending around weak and strong axis of principal beams. Traveller hoist horizontal vibrations are uncoupled from crane vibrations due to their low frequency compared to the crane eigenfrequencies. Nevertheless, there is a contribution of hoist load on vertical vibration of crane principal beams.

For isolated crane numerical model (a, b), vertical bending of crane principal beams is coupled with a translational motion along cross travel direction. This coupling is caused by bearing conditions imposed at crane support points, with South wheels modelled as free wheels on cross travel direction. This coupling of vertical and cross travel oscillations is imposed by numerical analysis and does not represent a real dynamic response of the crane.

Crane-support structure interaction modes

For model including both crane and steel frame carrying structure (c), additional eigenmodes appear, that represent crane-carrying structure interaction.

On long travel direction, the fundamental mode involving overhead crane is the fundamental mode of steel frame carrying structure that induces a translational rigid body motion of the crane. Eigenfrequency and modal shape are the same for all crane configurations: there is no coupling of the response of crane and support structure along long travel direction.

Vertical and cross travel interaction modes show the coupling of crane and support structure response. Fundamental mode along the cross travel direction is a bending of North runway beam around weak inertia axis that induces a rigid body translational motion of crane. Eigenfrequency associated to this mode depends on the crane trolley configuration. Moreover, if we compare modal analysis results of steel frame carrying structure without the crane (a) and with the crane (b, c), a shift in frequencies can be observed. Overhead crane modifies steel frame modes and vice-versa.

For modes along vertical direction, interaction phenomena are observed. There is a coupling of crane and runway beam response. Bending around strong inertia axis of runway beams induces a vertical motion of crane supports. Some modal shapes show that vertical bending of runway beams induces differential vertical motion of North and South long travel tracks. These phenomena are amplified for configurations with crane located at mid span of runway beam.

SEISMIC RESPONSE

Floor response spectra

Accelerations at overhead crane supports are represented by floor spectra at runway level on Fig. 5. Floor spectra show the influence of crane on steel frame carrying structure response as well as the anisotropic character of response of crane-carrying structure system.

Horizontal response at runway level is reduced compared to ground input motion. Peak floor acceleration (PFA) at runway beam is between 0.07g and 0.08g along long travel direction, compared to 0.12g peak ground acceleration (PGA). Carrying steel frame structure, with horizontal eigenfrequencies below 1.0Hz, acts as a low-pass filter of horizontal ground motion. On the contrary, vertical seismic response at runway level shows an important amplification of vertical PGA, with an amplification factor, PFA/PGA, between 2.0 and 3.4.

Long travel direction response spectra values are similar for all methods since crane and carrying structure can be considered as uncoupled systems. Multisupported nature of overhead crane has little influence in response since crane bearing conditions are symmetrical in this direction and motion of runway beams is in phase.

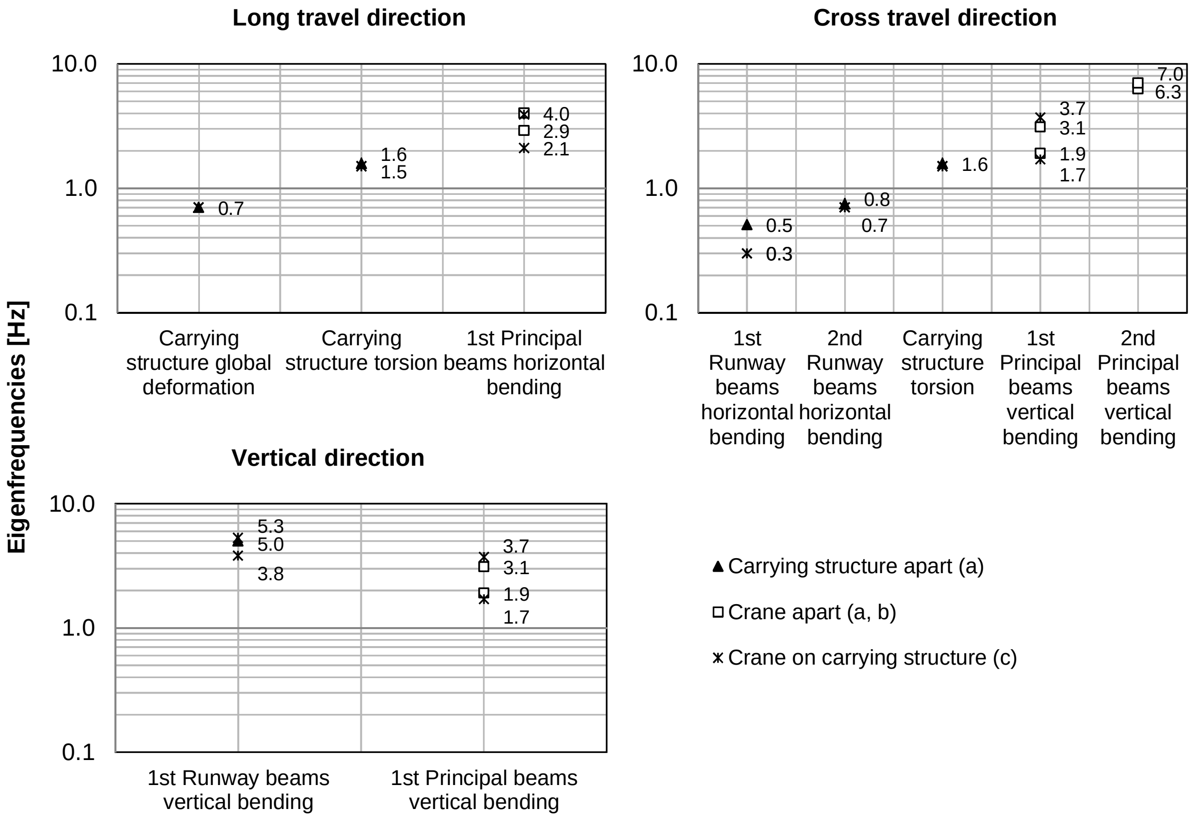

Figure 3. Eigenfrequencies for different models

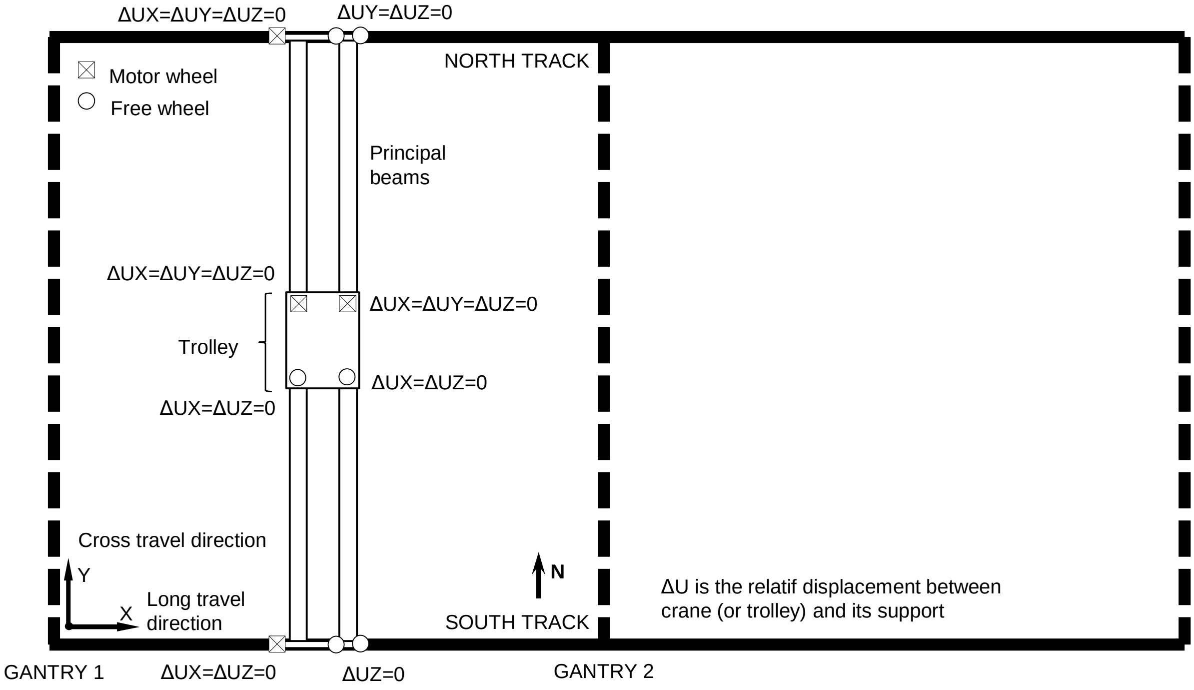

Figure 4. Bearing conditions of crane and trolley in numerical model

Cross travel floor response spectra show a shift in amplification frequencies and in response values. Floor response spectrum including dynamic interaction (c) is the highest for all frequencies. Crane multisupport arrangement has an important influence in tranversal response. Assymetrical bearing conditions on cross travel direction (North wheels are blocked along cross travel direction while South wheels are free) is equivalent to a loaded track with the entire crane mass and an unloaded track. This configuration is not well captured by a classical inertial coupled model (b), since it represents an equal repartition of loads from crane on both tracks.

Vertical floor response spectra depend as well on the modelling of interaction. Taking account of inertial interaction induces a shift on amplification frequencies. The system including crane mass (b) is globally more flexible, hence peak frequencies are lower that the ones for a system with no interaction (a). Taking account of dynamic interaction (c) induces a reduction of spectral response values compared to uncoupled (a) and inertial coupled responses (b).

Displacements and efforts

Differential displacements at support points of overhead crane illustrate crane-carrying structure dynamic interaction. Only results with dynamic coupled method (c) capture these displacements while with uncoupled (a) and inertial coupled methods (b), motion of support points is of same amplitude and phase.

Under seismic action, maximum relative displacement between tracks is equal to 13mm along long travel direction, to 75mm along cross travel direction and below 2mm along vertical direction. Relative displacements point out the coupling of long travel and cross travel direction of response due to torsion of the carrying frame structure.

Supports displacements, as introduced by dynamic coupled method (c), increase flexibilty of the crane system and induce rigid body motion of crane. Thus, seismic level associated to principal modes of crane system is lower and deformations of crane components (such as principal beams or end carriage beams) are reduced.

Displacements at mid-span of principal beams caused by their deformation are significantly reduced when dynamic interaction is taken into account. Vertical displacement at mid-span of principal beams is around 9mm for uncoupled method (a), 18mm for inertial coupled method (b) and 3mm for dynamic coupled method (c).

These results are directly correlated with efforts in crane components, such as bending moment on principal beams. For instance, under a vertical seismic action, maximum bending moment around strong inertia axis of principal beams (vertical bending) is equal to 1.2MNm for uncoupled method (a), 2.1MNm for inertial coupled method (b) and 0.8MNm for dynamic coupled method (c), which is equivalent to a reduction of maximum seismic vertical bending moment between 43% and 62%.

Under a horizontal seismic action parallel to long travel direction, maximum bending moment around weak inertia axis of principal beams (horizontal bending) is equal to 0.28MNm for uncoupled method (a) and for inertial coupled method (b) and 0.12MNm for dynamic coupled method (c), which is equivalent to a reduction of 57% of maximum seismic horizontal bending moment.

Resultant forces

Resultant seismic forces, quantified in terms of acceleration, illustrate the seismic level effectively induced in the overhead crane. Under long travel direction excitation, resultant force in this direction for methods (a) and (b) goes from 0.08g to 0.10g, which prooves the poor influence of inertial interaction in response. For dynamic coupled method (c), resultant force is 0.06g.

For cross travel direction excitation, resultant force for methods (a) and (b) varies between 0.14g to 0.20g, while for dynamic coupled method (c), it goes from 0.29g to 0.46g. The high value obtained with method (c) illustrates the importance of differencial displacements between crane wheels and track, that cannot be appropriately estimated with methods (a) and (b).

In the case of vertical excitation, resultant force for method (a) is between 0.15g and 0.25g while for method (b), it goes from 0.17g to 0.40g. Such difference comes from the variation of floor spectra values for uncoupled and inertial coupled models in the range of vertical fundamental frequencies of crane (Fig. 5). Vertical resultant force for dynamic coupled method (c) is the lowest, ranging from 0.09g to 0.14g.

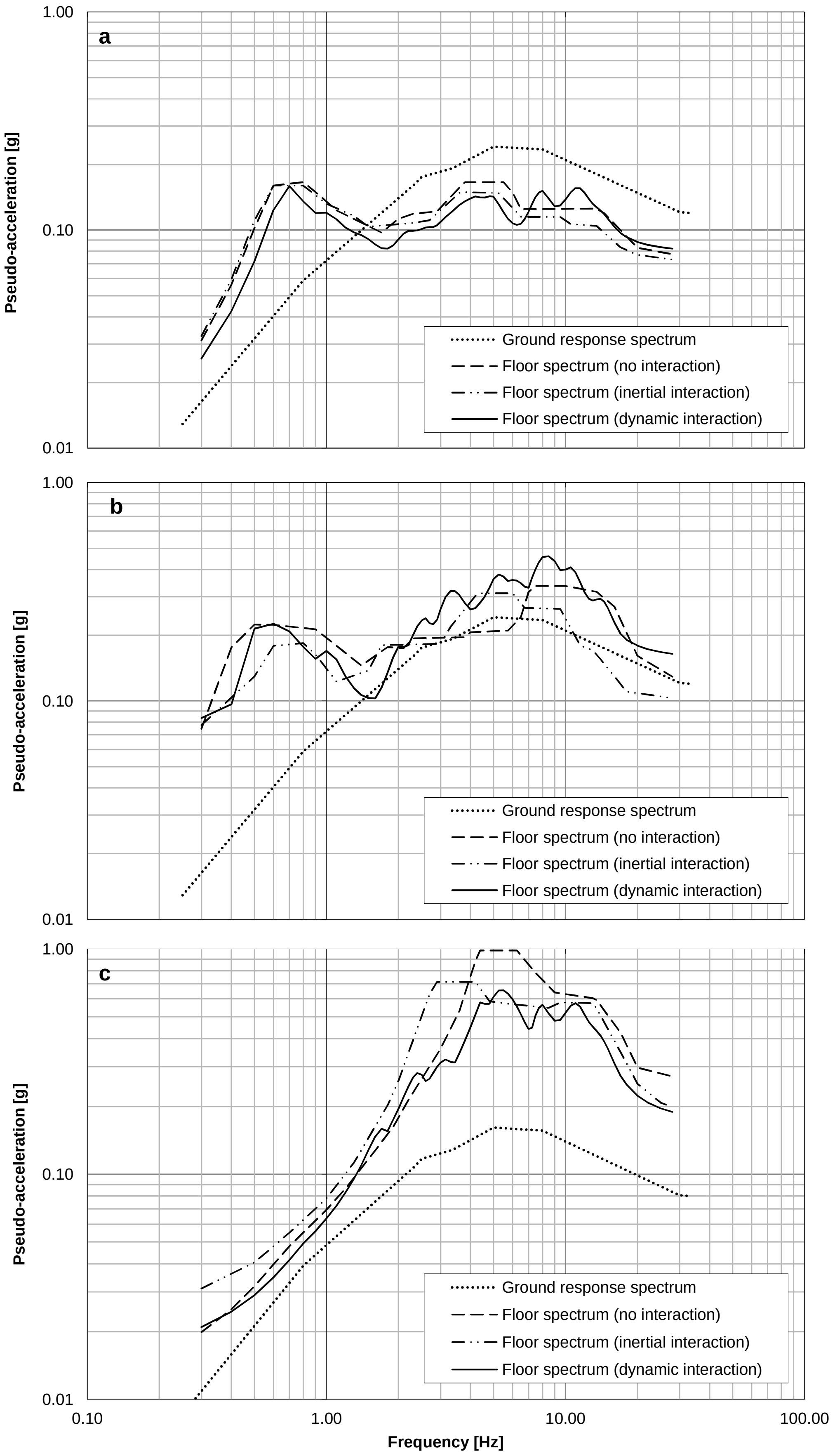

Figure 5. Floor spectra at runway level for 7% critical damping: a) response along long travel direction, b) response along cross travel direction and c) response along vertical direction

ULTIMATE LIMIT STATES OF STRENGTH AND STABILITY

Stability assessment

Stability assessment of crane and trolley concerns sliding along track, uplift and derailment. Fig. 6 show safety factors for different crane configurations and analysis methods. Results show that crane and trolley sliding along track is the most common instability during earthquake loading while uplift is rare. For these instability mecanisms, dynamic coupled method (c) turns out to be as the most favourable analysis method giving source to the highest safety factors.

Safety factor for uplift is calculated as specified in Eq.(2), where $F_{Z,\{G\}}$ is the vertical resultant force ($F_Z<0$ for uplift) of crane or trolley under dead loads and $F_{Z,\{G+E\}}$ under the combination of dead loads, G, and earthquake loads, E. The most unfavourable results concerning uplift of crane and trolley are obtained with inertial coupled method (b). The implementation of uncoupled method (a) represents a maximum increase in safety factors for crane uplift of 9% (20%, for trolley uplift) while the implementation of dynamic coupled method (c) induces an increase in crane uplift safety factors of 16% (44% for trolley uplift).

$$SF_{uplift} = 1 + \frac{F_{Z,\{G+E\}}}{F_{Z,\{G\}}} \tag{2}$$

With regard to crane sliding, dynamic coupled method results (c) are the most favourable since the seismic effect on long travel and vertical direction is reduced. Consequently, decompression of blocked wheels is limited and friction force is sufficient. The implementation of dynamic coupled method (c) results in an increase of safety factors ranging from 37% to 48%.

Derailment safety factor is evaluated as specified in Eq.(3), with $\Delta_{\{G+E\}}$ the relative displacement along cross travel direction between South track and South crane wheels and d the mean of the width of rail and wheel. Unlike for uplift and sliding, derailment safety factors are the lowest for dynamic coupled method (c).

$$SF_{derailment} = \frac{d}{\Delta_{\{G+E\}}} \tag{3}$$

Relative displacement between South track and South crane wheels is partly due to crane deformation and partly due to track displacement. For methods (a) and (b), results introduce the part of displacement due to the deformation of crane only, while tracks relative displacement cannot be taken into account since tracks are not represented in the numerical model. Therefore, estimated relative displacements out of dynamic coupled method (c) are higher and more precise than for the two other methods. Derailment risk assessment is hence not accurate when dynamic coupling is not taken into account.

Structural integrity

Structural integrity of overhead crane critical sections is examined, comparing yield stress of steel to maximum stress under the effect of dead loads and earthquake loads. Safety factor is defined in accordance with FEM 1.001 (1998). Parameters on Eq.(4) are yield strength of steel, σ_e; maximum axial stress on critical section, σ, and maximum shear stress on critical section, τ.

$$SF_{strength} = \min\left\{ \frac{\sigma_e}{\sigma}; \frac{\sigma_e/\sqrt{3}}{\tau}; \frac{\sigma_e}{\sqrt{\sigma^2+3\tau^2}} \right\} \tag{4}$$

Dynamic coupling method (c) produces the most favourable results for principal beams and end carriage beams critical sections, as displayed in Fig.7.

Regarding principal beams, inertial coupled method (b) is the most conservative, with safety factors between 1.9 to 3.5 for all configurations. Results obtained with uncoupled method (a) respresent an increase in safety factors between 5% and 16%. The implementation of dynamic coupled method (c) represents an increase in safety factors varying from 9% to 33%.

Concerning end carriage beams, uncoupled method (a) and inertial coupled method (b) results are alternatively the most conservative, depending on the configuration. Dynamic coupled method (c) results represent an increase of 13% to 41% on safety factors.

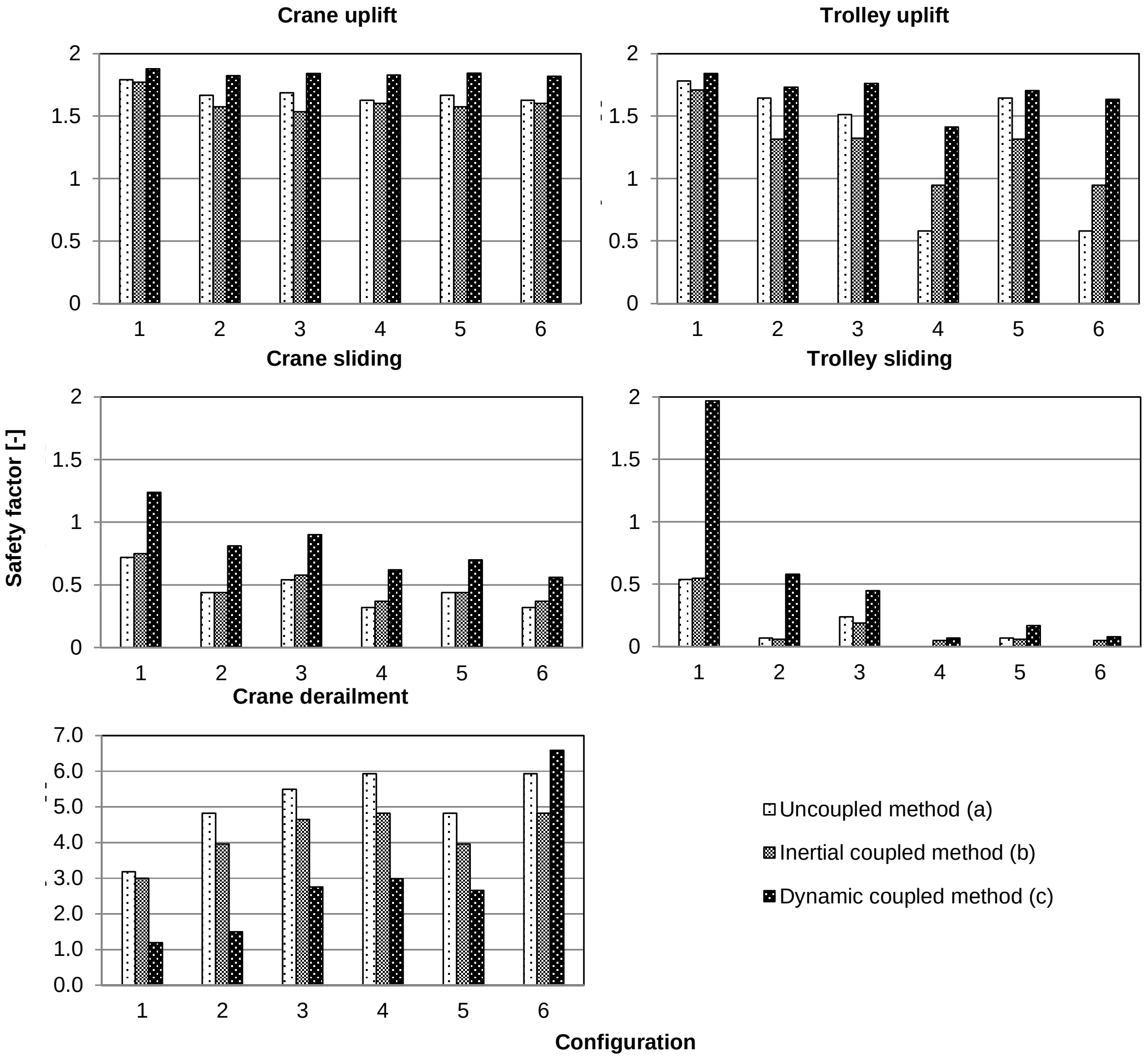

Figure 6. Stability criteria safety factors for all configurations

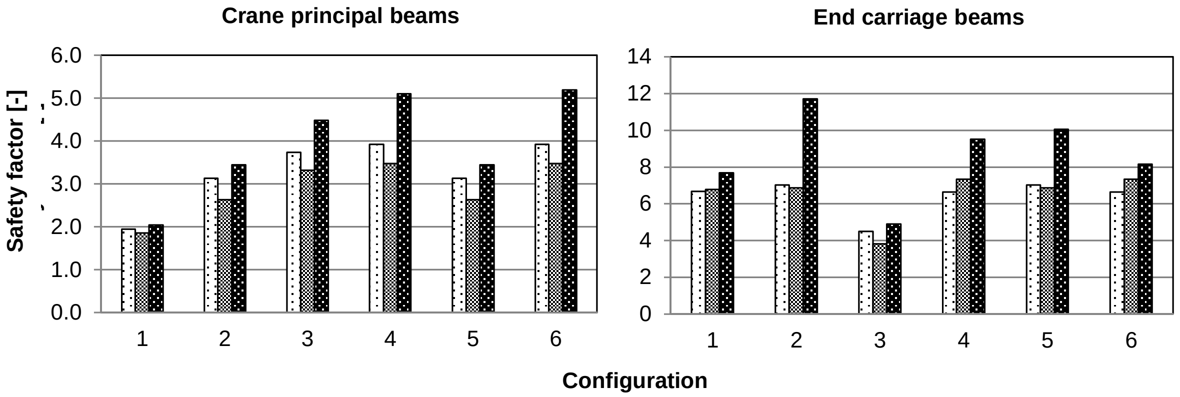

Figure 7. Structural integrity safety factors for all configurations

INTERACTION DOMAIN

An interaction domain can be defined in terms of mass and frequency ratios between crane and support structure (ASCE 4-98, 1998 and ASN/GUIDE/2/01, 2006). Interaction domain establishes the features of crane and carrying structure for which a coupling of response is observed. Interaction domains are well documented to one degree of freedom (DOF) equipment with a unique support point. In the case of overhead crane, interaction domain is properly fitted to dynamics features when the response is strongly monomodal.

Dynamic features of crane and carrying frame structure along different response directions are plotted on Fig. 8. Mass ratio, R_m, is the ratio of effective mass of crane and carrying structure fundamental mode in each direction. Frequency ratio, R_f, is the ratio of crane and carrying structure fundamental eigenfrequencies.

It appears clearly that long travel direction motion of crane and carrying structure are uncoupled since fundamental frequencies of crane and carrying structure are different and effective mass of fundamental mode of crane represents less than 10% of the effective mass of fundamental mode of carrying structure. In this direction, fundamental mode of carrying structure mobilizes the steel frame globally.

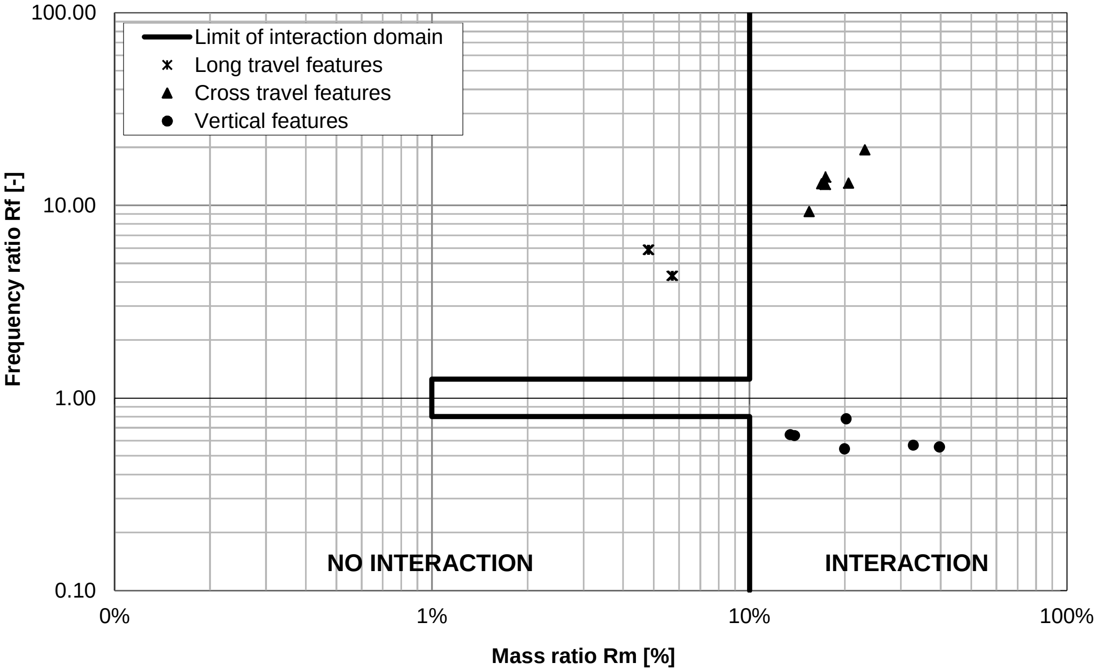

Figure 8. Interaction domain according to ASN/GUIDE/02. Crane and carrying structure dynamic parameters for all configurations

Vertical and cross travel features show that the response of crane and carrying structure is coupled, since carrying structure in these directions involves essentially runway beams, as the effective carrying structure of overhead crane. The mass of crane represents more than 10% of the effective mass of carrying structure.

Cross travel features illustrate crane as a rigid system compared to carrying structure due to the important flexibility of runway beams bending around weak inertia axis. However, inertial coupled method (b), as well as uncoupled method (a), leads to inaccurate results since it is considered that motion of both tracks are of same amplitude and phase. Yet differential displacements between both tracks are relevant, as is pointed out by dynamic coupled method (c) displacement results.

Vertical features of crane and carrying structure point out to a partial frequency uncoupling, since fundamental frequency of crane happens to be lower than carrying structure eigenfrequencies. When an equipment (i.e. crane) is flexible compared to its carrying structure, the influence of mass on the global system response is neglectable. Dynamic coupled (c) and uncoupled (a) vertical response spectrum at runway level in the range of crane eigenfrequencies (from 1.9Hz to 3.1Hz) are strikingly similar (Fig. 5). Furthermore, inertial coupled (b) vertical response spectrum values in the same frequency range appear to be significantly higher. Hence inertial coupled method (b) leads to over-conservative results on vertical direction.

CONCLUSIONS

Evaluating the seismic response of an equipment (i.e. overhead crane) attached to a carrying structure (i.e. steel frame) requires a preliminary analysis of their modal features and the definition of the “effective” carrying structure for each direction. The influence of crane-carrying structure interaction in seismic response of overhead crane is strongly correlated to the response direction, as a result of the anisotropy of bearing conditions and carrying structure behaviour.

Long travel direction seismic responses of crane and carrying structure are uncoupled since modal features remain constant for all models. In this direction, the entire steel frame carrying structure acts as a 1-DOF flexible oscillator, with low fundamental frequency of vibration (around 0.7Hz) compared to overhead crane fundamental mode.

Cross travel seismic response is complex, since significant inertial and kinematic interaction is produced. The effective carrying structure depends on the position of overhead crane. When the crane is located at mid-span of runway beams, effective carrying structure is composed mainly by North runway beam (bending around weak axis) and when the crane is located above gantry, effective carrying structure is composed by runway beam and gantry. Furthermore, dissymetric bearing conditions with regards to crane tracks introduce differential displacements between tracks that can only be determined when carrying structure is modelled.

Vertical seismic behaviour of crane-carrying structure system depends on excitation frequency. For fundamental frequencies of crane, in the range of 2Hz to 3Hz, only kinematic interaction takes part, while for higher frequencies, above 4Hz, inertial interaction controls the response. Effective carrying structure concerns runway beams bending around strong inertia axis.

Results attest that a correct implementation of crane-carrying structure interaction leads to a reduction of seismic efforts and hence an increase of safety factors regarding integrity (up to 16% for end carriage beams and 33% for principal beams) and of safety factors regarding stability (up to 16% concerning crane uplift and 48% concerning crane sliding). The quantified differences between methods include the conservatism introduced by the broadening of floor spectra for uncoupled method (a) and inertial coupled method (b). Furthermore, relative displacements between wheels and track on cross travel direction can only be obtained with a model including carrying structure (c).

A preliminary analysis of modal features of primary system and subsystem is useful to identify the importance of interaction as well as to define the effective carrying structure at each direction. A dynamic coupled spectrum analysis carried out on a model including the equipment and the effective carrying structure (i.e. runway beams) should lead to satisfactory results with efficient time-machine resources.

Interaction domains defined for 1-DOF subsystems can be useful to characterize the fundamental mode of vibration yet they are inadequate to describe accurately the seismic behaviour of the system.

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