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Seismic Behavior of a Jumbo Container Crane in the Low Seismicity Zone Using Time-History Analyses

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***Abstract*—**Jumbo container crane is an important part of port structures that needs to be designed properly, even when the port locates in low seismicity zone such as in Korea. In this paper, 30 artificial ground motions derived from the elastic response spectra of Korean Building Code (2005) are used for time history analysis. It is found that the uplift might not occur in this analysis when the crane locates in the low seismic zone. Therefore, a selection of a pinned or a gap element for base supporting has not much effect on the determination of the total base shear. The relationships between the total base shear and peak ground acceleration (PGA) and the relationships between the portal drift and the PGA are proposed in this study.

***Keywords*—**Jumbo container crane, portal drift, time history analysis, total base shear.

I. Introduction

EARTHQUAKE is one of the destroying natural disasters that impact on infrastructures, human life, and the economy. In the history, there were several major earthquakes, such as Long Beach in 1933, Alaska in 1964, Northridge in 1994 in America; Mexico city earthquake in 1985, Japan Hyogo-ken Nanbu earthquake in 1995, or in Haiti in 2010 [1]-[4], that killed many people and destroyed buildings, bridges, pipelines, and harbor structures as well. The effect of seaports has been shown to be considerable on the economy because water transportation remains a large carrier of freight in the world. The container crane, an important component of seaports, is usually susceptible to damage when it suffers from earthquake events [5]. In addition, the size and weight of modern jumbo cranes are rising to satisfy with the demand for bigger ships. As a result, the seismic forces are much larger when the crane increases its size. Recently, there are several low to moderate earthquakes occurring in Korea; these disasters warn us to pay attention to seismic design more than ever, especially for larger-scale structures.

The rocking-type response of a jumbo container crane is closely coupled with an uplift and derailment at higher excitation levels. However, in low seismicity zones, the behavior is just “shaking” with slightly or without uplift. A pinned base and a gap element base support are possible to be used for seismic analysis. Currently, methods for seismic analysis of crane structures such as simplified analysis (response spectrum method), simplified dynamic analysis (pushover analysis), and dynamic analysis (time history analysis) are recommended in most of the previous studies and design guidelines [2], [6], [7]. The response spectrum method is suitable for linear analysis, while the pushover and time history analysis can consider the nonlinear behavior. The advantage of the time history analysis is that it provides the most accurate value than other methods, but it is time- and cost-consuming. In this study, a three-dimensional (3D) finite element model was built by using SAP2000 software package. Acceleration time history analysis is applied throughout 30 different artificial ground motions generated from the response spectrum of Korea Building Code [8]. The study aims to obtain the total base shear, uplift, and drift of the portal frame of the crane. Then, the relationship of the base shear and the drift are established with the PGA.

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II. Numerical Simulation

A. Model of the Jumbo Container Crane

The container crane has a span/gage distance of 30.48 m, a total height of 60.69 m, an outreach of 65 m and a clearance of portal of 18.29 m. Data are based on the research of Kosbab [5]. The portal frames are made by stiffened hollow box-sections, tubes, and wide-flange shapes meeting the ASTM A709 Grade 50 requirements [9]. The 3D model of the container crane is shown in Fig. 1.

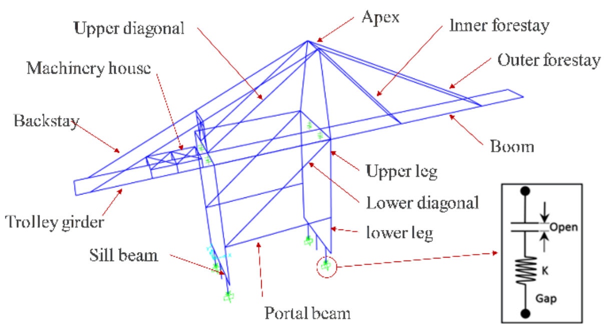

Fig. 1 3D model of jumbo container crane

Out of the weight of the structure itself, the weight of nonstructural facilities is significant. All the external loads are from operation facilities such as stairs, trucks, machinery house, ½ festoon, snag device, etc. Total weight of both structural and nonstructural is shown in Table I.

TABLE I
TOTAL WEIGHT OF JUMBO CONTAINER CRANE

No.	Items	Weight (kN)
1	Structural frame	9070.37
2	Nonstructural loads	3264.55
	Total	**12334.92**

B. Cross Section of Major Elements

This container crane is made by a combination of three types of steel: Hollow boxes, tubes, and wide-flange shapes [5]. The portal frame elements are hollow boxes, except for the lower diagonal elements as tubes as seen in Fig. 2. The details cross sections of some major elements of the portal frame are summarized in Table II, whereas B and D are the outside dimensions, t_f and t_w are the flange and web thicknesses, respectively.

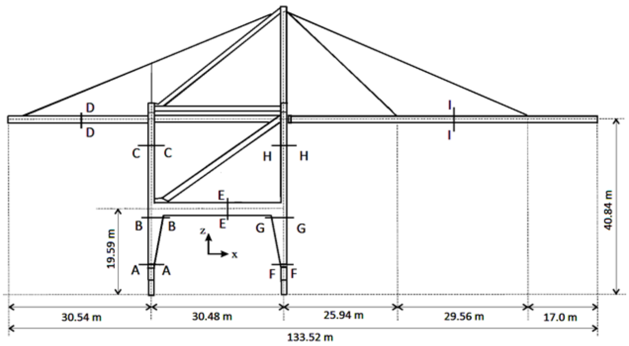

Fig. 2 Overview of Jumbo container crane

TABLE II
DIMENSIONS OF HOLLOW BOX SECTIONS

Section	B [m]	t_f [cm]	D [m]	t_w [cm]
A-A	1.34	1.6	1.73	1.6
B-B	2.83	2.6	1.73	1.4
C-C	1.34	1.2	1.72	1.0
D-D	1.52	1.3	2.29	1.0
E-E	1.72	1.2	3.02	0.8
F-F	1.34	2.4	1.75	2.0
G-G	2.84	2.0	1.74	2.0
H-H	1.34	2.0	1.74	1.6
I-I	1.52	1.6	2.29	1.0

C. Boundary Conditions

In analyzing crane structures, there are two types of boundary conditions used that are pinned and gap elements. However, the wheels of a container crane are not generally positively tied to the crane rails or wharf deck. Therefore, it is possible for the wheels to uplift from the rail [5].

A pinned boundary is used when there are no uplift and derailment. Therefore, there is no computational limit to the range of reaction either in vertical or horizontal direction. The pinned boundary is adequate to use in case of no uplift occurrence. On the other hand, when the legs of a container crane are tied down to the ground in large wind seasons such as hurricanes and typhoons, a pinned support would be a reasonable choice of boundary model for analysis of wind resistance. In this research, a gap link is used as illustrated in Fig. 1 that reflects the contact between trucks and rail in operation. This is activated when structures come closer and deactivated when they go far away; it means that gap link is only compressed. It is suitable for analyzing the uplift behavior of the crane in operation without anchor fixing. The gap element does not remove itself the horizontal direction during uplift events since derailment is not possible to analyze [10].

D. Input Ground Motions

Artificial ground motions are derived from the elastic response spectra of Korean Building Code [8]. From two seismic zones (Z1 and Z2) and five soil classes (i.e. S_A for hard rock, S_B for rock, S_C for very dense soil and soft rock, S_D for stiff soil, and S_E for soft soil), ten different elastic response spectra with 5% damping are developed based on the guidelines of KBC as indicated in Fig. 3. The results of elastic response spectra are shown in Fig. 4.

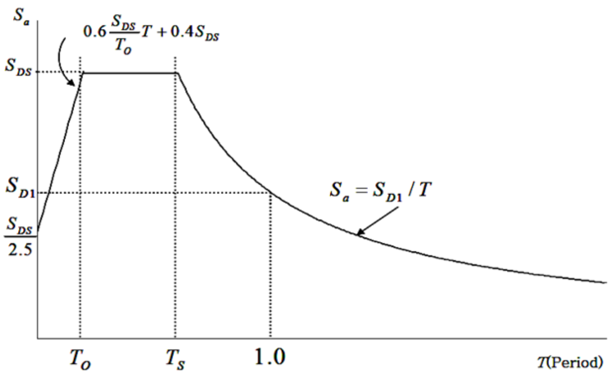

Fig. 3 Guidelines of Korea Building Code (KBC) for constructing the design response spectrum

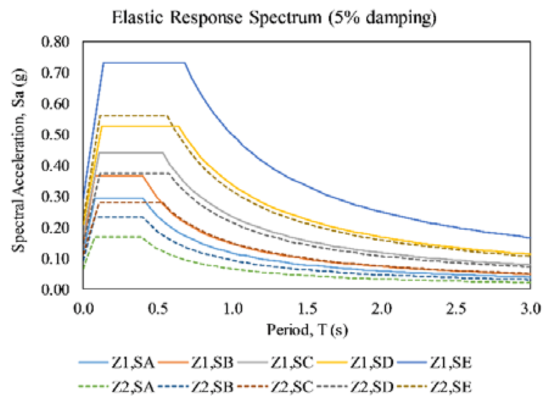

Fig. 4 Elastic response spectrum developed from KBC 2005

Then, three different artificial ground motions are generated from each pair of the seismic zone and soil class using QuakeGem program [11], which is based on the spectral-representation-based simulation algorithm proposed by Deodatis in 1996 [12], [13]. Thus, 30 artificial ground motions are generated and applied to the 3D model in this study.

III. Dynamic Analyses

A. Method of Analysis

In this study, the time history analysis is used based on the direct-integration method using SAP2000. The equation of motion shown in (1) is solved by the Hilber-Hughes-Taylor (HHT) method. The nonlinearity material and P-Delta effect are considered.

$$M.\ddot{u}(t) + C.\dot{u}(t) + K.u(t) = F(t) \qquad (1)$$

where M, C, and K are the mass, damping, and stiffness matrix, respectively; u(t) is the relative displacement vector, and F(t) is the applied force which is given by a set of discrete values $f_i = f(t_i)$, i = 0 to N.

B. Total Base Shear

The total base shears obtained from 30 artificial ground motions are plotted in Fig. 5. All the data points are well fitted with a linear relationship between the total base shear and the PGA, with the R-squared value of 0.937.

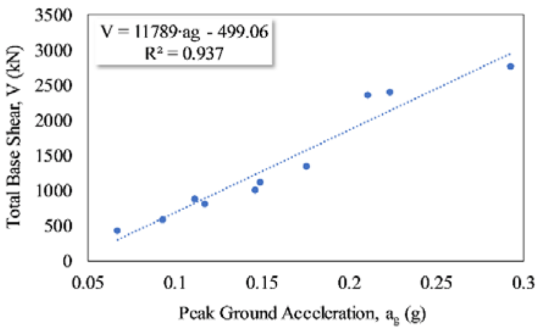

Fig. 5 Total base shear and PGA

The relationship from Fig. 5 or (2) can help to predict the total base shear for the preliminary elastic seismic design of the same type of the crane structure:

$$V = 11789 \cdot a_g - 499.06 \qquad (2)$$

where V is the total base shear (kN) and a_g is the PGA (g).

C. Drift of the Portal Frame

The drift at the top of the portal frame of a container crane provides information about how much of the horizontal deformation occurs in the portal frame when the crane deforms based on the fundamental mode in the trolley travel direction. It is noted that the portal drift is not the drift of the whole frame structure. In order to measure the drift of the whole structure, the horizontal displacement should be measured at the top of the upper leg. However, in the past experiences, most of the plastic hinges developed dominantly in the crane structures at the portal frame. So, the horizontal displacement or drift at the top of the portal frame is commonly considered [14]. In this study, the portal drift is determined at node 136 (with a portal height of 19.59 m). The maximum drift of the portal frame is 0.69% at 11.91 seconds in trolley travel direction for the ground motion generated from the seismic zone 1 and soil class SE (with a PGA of 0.293 g), as shown in Fig. 6.

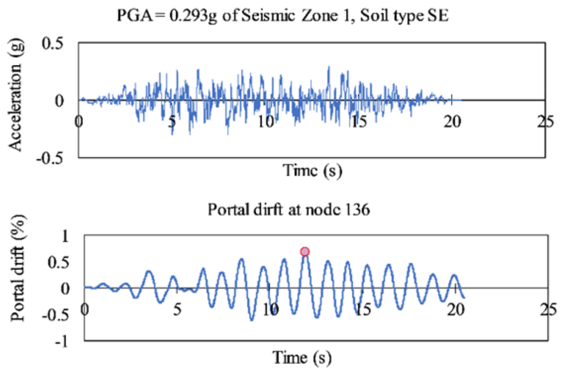

Fig. 6 Portal drift on node 136 under seismic Z1SE

Based on Kosbab's research work [5], the capacity curve obtained from pushover analysis shows that the initial yielding point in portal and top of lower leg occurs when portal drift is approximately 2% [5] and a potential complete collapse at a drift of about 4.5%. Under the impact of the maximum ground motion in this study (Z1SE with the PGA of 0.293 g) the portal frame is deformed with a drift of 0.69% approximately. Thus, the crane is expected to work in the elastic state. The relationship between PGA and portal drift is constructed as shown in Fig. 7. It is well fixed with linear regression (R^2 = 0.898). The equation of the relationship is as follows:

$$drift = 2.8796 \cdot a_g - 0.1242 \qquad (3)$$

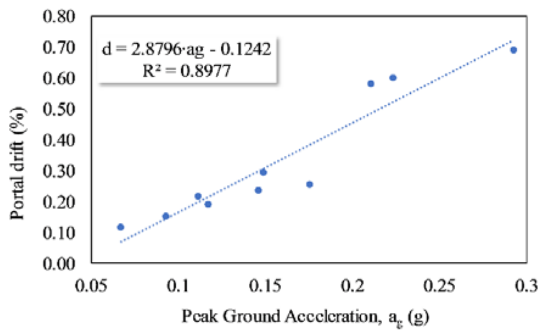

Fig. 7 Portal drift vs PGA

D. Uplift Response

The uplifting of the crane's legs will redistribute the load and horizontal displacements of the legs. When the weight on the legs was decreased, the friction holding crane legs on the ground was also reduced, the legs moved inward and outward in both horizontal and vertical directions, since the uplifted leg is very difficult to determine, and the contact forces are changed. Therefore, a gap element is used for this analysis as mentioned above. In this analysis, we consider uplift response for two landside legs (node 128 and 130), waterside legs (node 122 and 124, as shown in Fig. 8. Out of four nodes, the node

128 shows the maximum vertical movement of -0.00007 m very close to zero at 11.93 seconds at the PGA of 0.293 g, indicating that the uplift might occur in the landside legs if the structure receives a larger earthquake. However, the crane is not uplifted under Korean artificial ground motions. In addition, center of total mass is not in the center of the two portal legs, it is closer to the waterside legs than the landside legs. Therefore, the first uplift might occur in the landside legs, same as the uplift analysis of this study.

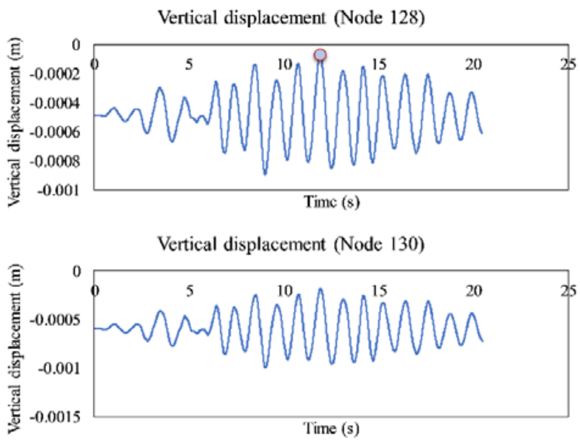

Fig. 8 Vertical displacement of landside legs under arttificial ground motion Z1SE

IV. Conclusion

In this study, 3D numerical simulation of container crane is analyzed by time history acceleration analysis under 30 artificial ground motions generated from the elastic response spectra of Korean Building Code.

The results show that uplift does not occur, therefore, both pinned and gap base support can be used for dynamic analysis of a jumbo container crane in low seismicity zones without sacrificing much accuracy. A relationship between PGA and total base shear is proposed in this study to predict the total base shear in the preliminary elastic seismic design of the jumbo container crane. In addition, under Korean artificial ground motions, portal drift is low, indicating that the crane structure works in elastic limit.

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