EFFECTS OF BOUNDARY CONDITION ON SEISMIC PERFORMANCE OF CONTAINER CRANE

ẢNH HƯỞNG CỦA ĐIỀU KIỆN BIÊN TỚI PHẢN ỨNG ĐỊA CHẤN CỦA CẨU HÀNG CONTAINER

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ABSTRACT: Container crane structure plays a crucial role in loading and unloading goods from a container ship to harbors. In any case, a breakdown of the container crane would harm the economy of a country. The modern crane is bigger to satisfy the demand of the owner; therefore, it is less stable under seismic excitation. Engineers often encounter an issue for choosing the boundary condition of the simulated model of the container crane as the legs can be uplifted or derailed under strong earthquakes. In this case, the simple work of pinned boundary condition can be replaced by the elastic-no-tension element between the structure and the ground. In this way, the leg base is free to move in vertical direction, and its vertical reaction reduces to zero. The objective of this paper is to evaluate the seismic performance of a container crane by the time history acceleration analysis using two different base supports, i.e., pin and elastic-no-tension supports. Firstly, horizontal response spectra of actual earthquakes are adjusted by scaling the amplitude of each ground motion to coincides with a specific target spectral acceleration at the fundamental period of the container crane and then determined the scale factor. Afterwards, the ground motions are generated based on the scale factor, and they are used as input data for dynamic analysis by time history method. Two cases of target spectral accelerations will be determined to evaluate the dynamic responses of structure for uplift and no uplift phenomenon. Some response characteristics, i.e., total base shear and portal drift, are investigated. From that, the results show that the elastic-no-tensions supports are suitable for simulating the real behavior of the container crane when it is analyzed under high seismic excitation.

KEYWORDS: container crane, boundary condition, total base shear, portal drift, uplift, vertical reaction.

TÓM TẮT: Kết cấu cẩu hàng container đóng vai trò quan trọng trong việc bốc dỡ hàng hóa từ các tàu chở hàng container tới bến cảng. Trong mọi trường hợp, một sự cố cho cẩu hàng container sẽ gây ảnh hưởng cho nền kinh tế của một quốc gia. Kết cấu cẩu hàng ngày nay được yêu cầu phải lớn để đáp ứng nhu cầu của chủ sỡ hữu do đó càng dẫn đến sự mất ổn định dưới tác dụng của địa chấn. Các kỹ sư thường gặp phải vấn đề trong việc lựa chọn điều kiện biên cho mô hình mô phỏng do chân cẩu có thể nâng lên hoặc trật bánh khi gặp phải động đất mạnh. Trong trường hợp này, mô hình điều kiện biên bằng gối cố định có thể được thay thế bằng phần tử đàn hồi không lực căng giữa kết cấu và đất. Bằng phương pháp này, chân cẩu có thể di chuyển tự do theo phương thẳng đứng, đồng thời phản lực thẳng đứng sẽ giảm về không. Mục tiêu của bài báo là đánh giá phản ứng địa chấn của kết cấu cẩu hàng container bằng phương pháp phân tích theo lịch sử thời gian trận động đất khi sử dụng các mô hình điều kiện biên: bằng gối cố định và phần tử đàn hồi không lực căng. Đầu tiên, phổ phản ứng ngang của các trận động đất thực tế được điều chỉnh bằng cách điều chỉnh biên độ của từng phổ phản ứng trùng với gia tốc phổ mục tiêu tại chu kỳ cơ bản của cần cẩu container, từ đó hệ số điều chỉnh sẽ được xác định. Tiếp theo, chuyển động mặt đất sẽ được điều chỉnh phụ thuộc vào hệ số, và các chuyển động được điều chỉnh sẽ được dùng làm dữ liệu cho phân tích động bằng phương pháp phân tích theo lịch sử thời gian. Hai trường hợp gia tốc phổ mục tiêu sẽ được xác định để đánh giá phản ứng động của kết cấu khi có và không có hiện tượng nâng lên. Các thuộc tính như lực cắt đáy, độ lệch của khung cổng sẽ được khảo sát. Từ đó, kết quả cho thấy phần tử đàn hồi không có lực căng phù hợp để mô phỏng điều kiện biên cho kết cấu cẩu hàng container khi phân tích với kích thích địa chấn mạnh.

TỪ KHÓA: cần cẩu container, điều kiện biên, lực cắt đáy tổng, độ lệch khung cổng, nâng lên, phản lực thẳng đứng.

1. INTRODUCTION

Container cranes continue growing in the size and numbers to handle the freightage increasing. The modern container cranes are triple size than the original ones, making them heavier and more vulnerable under seismic excitation [1]. From previous reports, failure of container cranes occurred in four modes: uplift and derailment as the wheels lift up off the rails and transfer in the horizontal direction; local buckling of the legs; yielding of tie downs; and overturning. The uplift phenomenon represents that the legs (wheels) of container crane lift up out of crane rails and move free in both vertical and horizontal direction under seismic excitation. As a result, the load will increase on the opposite leg. A crane at rest is fixed to rails with clamps or anchors, whose strength provides the upper limit for the crane resistance against external forces. In the United States, the design guidelines give a strong assumption: the design seismic load only creates incipient uplift for a crane [2]. That assumption is suitable for the previous container cranes that had small gage lengths and light weight, and thus could overturn over at relatively low lateral loads. As a result, U.S. port designers typically adopt a lateral seismic design load of 0.2 g for new container cranes [3]. However, cranes in operation are not supported by clamps or anchors, and the lateral resistance of the crane against external forces is from the friction and the wheel flanges [4]. During the Kobe earthquake in 1995, several cranes were damaged in the portal frame, even completely collapsed, where the uplift was determined as a direct cause of collapse for the failed cranes [5]. Thus, the boundary condition of the numerical model needs to be developed to accurately capture real responses of the container crane under seismic excitation.

Not many studies about the response of the container cranes under strong seismic excitation are published, and even less about the uplift phenomenon. For a better understanding of the dynamic response of container cranes, especially their uplift behavior, the response of container crane should be investigated by numerical and experimental methods. Some researchers analyzed both numerical and experimental models, for example, Laura D. Jacobs et al. [6] investigated the seismic response of jumbo container cranes by a shake table experiment and numerical model (both 2-D and 3-D) using the finite element method (FEM). C. Oktay Azeloglu et al. [7] also studied dynamical response of container crane by both experimental (a shake table test) and numerical methods, the authors concluded that the dynamical behavior of container crane including time and frequency domains could be done by an experimental method or a numerical method (using FEM).

FEM has some advantages to simulate the seismic response of container cranes. However, if the legs of a crane are uplifted under seismic excitation, the point at which the uplifted leg is very difficult to predict, and the contact forces between wheels and crane rails are always fluctuating because of changing of the contact configuration between the wheels and crane rails. Moreover, the stiffness and the frictional properties of the contact point are vary, which depend on how the wheel and the crane rail contacts each other. Therefore, it is difficult to accurately analyze the seismic behavior of the crane without a special modeling of the contact problem between the wheels and cranes. However, the difference of the boundary condition model was not shown in previous research. There were some models that were often used, such as a pin, fixed, elastic-no-tension element, frictional contact. It is questionable whether there need to be a a special model, or it is a simple model, i.e. pin, fixed, roller support to simulate boundary conditions of the container crane.

In this study, the boundary condition was investigated by SAP2000. Two models, i.e. Pin support and elastic-no-tension element, were used to simulate the link between wheels and crane rails (ground). Pin support can resist both vertical and horizontal forces, but they cannot resist moment. The pinned boundary is simple and available in all structural software, so it is an attractive choice. Using this support to simulate the interaction of wheels and crane rails means that neither uplift nor derailment is permitted. It can be used for a case of static analysis or when the uplift is not essential. When a pinned support is used, a simple check should be done to ensure that all vertical reactions of supports throughout the analysis remain compressive. The elastic-no-tension element is used to allow uplifting. It allows to develop compressive vertical reaction, but no tensile reaction. In other words, the elastic-no-tension element allows the legs to move freely in the vertical direction, so uplift event of the crane can capture by this element. The elastic-no-tension element is defined by Gap element in SAP2000 that Tran et al.[8] used in their study which compared the Nonlinear static and Time history analyses of a typical Korean STS container crane. The authors showed that uplift response of crane could be simulated by the Gap element. The result was nearly the same for nonlinear static and time history method. The Gap element used to simulate the interaction of wheels and crane rails represents that the uplift can occur while derailment is not permitted.

Total base shear, vertical reaction and portal drift will be determined to evaluate the effect of other boundary conditions to the response of container crane. Since a suitable model for boundary condition of container crane should be proposed for analyzing seismic load.

2. NUMERICAL SIMULATION

2.1. Modelling of a Jumbo Container Crane

In this study, a jumbo container crane was modeled by SAP2000 with the properties that were the same as those of the real crane. The simulated model has a height of 77.82 m from the ground to top of the container crane. The length from the end of the trolley girder to the end of the boom is around 136 m. The portal frame has a width span of 30.48 m and its height of 17.5 m. The numerical model has 9916 elements consisting of 9912 frame elements and 4 elements for the interaction of wheels and crane rails. The structural components are made of built-up stiffened box-sections and tubes. Since the mass of simulated model includes the self-weight of the structure and the weight of nonstructural facilities, i.e. machinery house, drive trucks, stowed pin, snag device, boom hoist rope, they are simulated as concentrated or distributed loads. These loads were analyzed simultaneously with the weight of the structure. The total weight of simulated models was 13883 kN, as shown in Table 1. The container crane are made of the SM490YB steel for main structure and the STK490 steel for pipe and tubes elements, and their material properties of the simulated model in SAP2000 are represented by yield stress $\sigma = 355$ N/mm^2, density $\rho = 7850$ kg/m^3, elastic modulus E = 200 GPa, Poisson's ratio $\mu = 0.3$, respectively. The model of the container crane is shown in Figure 1.

Table 1. Total weight of container crane

No.	Items	Weight (kN)
1	Structural frames	11030
2	Nonstructural loads	2853
	Total	13883

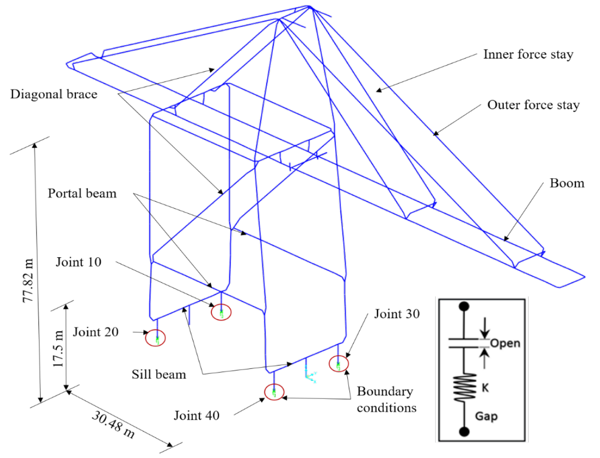

Figure 1. 3D model of container crane

2.2. Boundary Conditions

As mentioned above, the response of the crane legs under seismic excitation is a complicated phenomenon. The contact between the crane wheel and rail could be a pin support in normal conditions. However, pin support is not suitable for simulating the dynamic response of container crane coupled with uplift and derailment. In this study, Pin support and elastic-no-tension element was investigated by SAP2000 to compare the difference between the two investigated base boundaries. Elastic-no-tension element is defined by Gap element in SAP2000, as shown in Figure 1. Property of this element is illustrated in equation (1).

$$F = \begin{cases} k(d + open) & \text{if } d + open < 0 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Here, k is the spring constant, and the "open" is the initial gap opening. In this study, the "open" must be equal to zero because of the contact of wheels and crane rails before having a seismic load. All internal deformations are independent. The opening or closing of a gap for one deformation does not affect the behavior of the other deformations. This element only works in compression, it means that the element will be deactivated if the vertical reaction of legs is tensile. In other words, the legs can move freely in the vertical direction, but the legs cannot move in the horizontal direction. Therefore, the uplift phenomenon of crane's legs can be captured purely. The stiff spring constant (k) is recommended to be from 8756 to 52538 kN/cm (5000 to 30000 kips/in) [9]. Besides, several studies also shown the response of the structure to be insensitive to changes in the impact spring stiffness by one order of magnitude. In this study, a value of 43781 kN/cm (25000 kips/in) was chosen for the linear spring stiffness in the vertical direction.

Table 2. Boundary conditions of finite element model

Joints	Gap (Pin)					
	Force			Moment		
	U1	U2	U3	R1	R2	R3
10	1 (1)	1 (1)	0 (1)	0 (0)	0 (0)	0 (0)
20	1 (1)	1 (1)	0 (1)	0 (0)	0 (0)	0 (0)
30	1 (1)	1 (1)	0 (1)	0 (0)	0 (0)	0 (0)
40	1 (1)	1 (1)	0 (1)	0 (0)	0 (0)	0 (0)

Table 2 shows the characteristics of the boundary conditions of two models (Pin and Gap). Four joints in the model (Joint 10, 20, 30, and 40, as shown in Figure 1) are restrained to simulate the links of the crane rail and the wheels of the container crane.

Note that, in Table 2, the number "1" describes restrained and the number "0" shows free. The values in the parenthese indicate the Pin model. U1, U2, U3 represents the degree of freedom along x-axis (from landside leg to seaside leg), y-axis (along the rail) and z-axis (the gravity) directions, respectively; R1, R2, R3 represent the degree of the freedom for rotation around x-axis, y-axis and z-axis, respectively.

2.3. Ground Motions

Seismic ground motions selected for this study are therecoded ground motions taken from Pacific Earthquake Engineering Research Centre (PEER). Six ground motions data are shown in Table 3. The original response spectra of these ground motions are shown as Figure 2. The horizontal

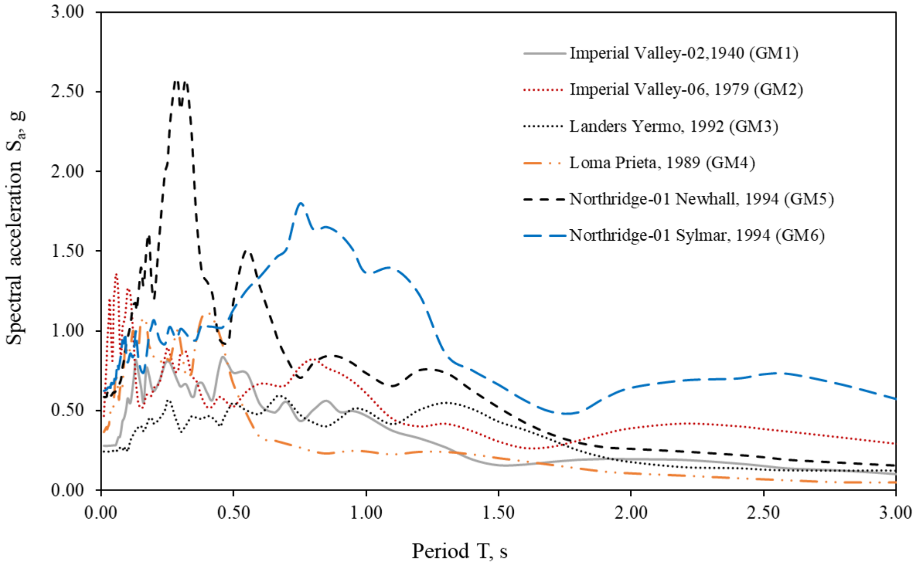

Figure 2. Original response spectral accelerations

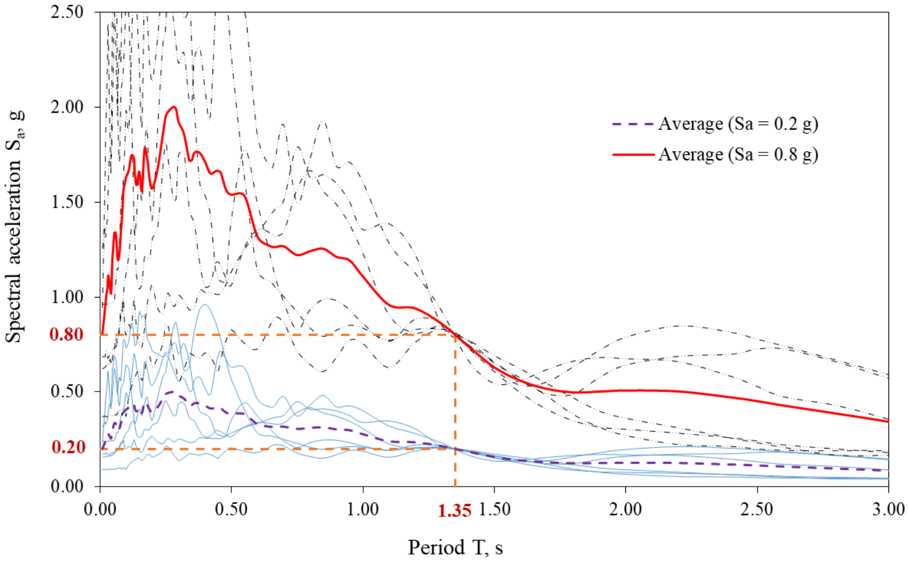

Figure 3. Scaled response spectrum at the fundamental period

Table 3. Ground motion from PEER

Ground motion	Earthquake	Year	Station	Magnitude	PGA (g)
1	Imperial Valley-02	1940	Elcentro Array #09	6.95	0.28
2	Imperial Valley-06	1979	Elcentro Array #06	6.53	0.45
3	Landers	1992	Yermo Fire Station	7.28	0.24
4	Loma Prieta	1989	Gilroy - Gavilan Coll	6.93	0.36
5	Northridge-01	1994	Newhall - Fire Sta	6.69	0.58
6	Northridge-01	1994	Sylmar - Converter Sta	6.69	0.62

accelerations of these ground motions were applied in trolley direction at the base level. The seismic load assigned in this direction has more effective on the dynamic response of crane, thus may cause the most damage to the structure. In this study, the uplift event of the crane was evaluated, therefore, the ground motion needs to be strong enough to make the legs of the crane lifted. K. A. Porter [10] introduced a method to increase the intensity of earthquakes. The method depends on the spectral acceleration (S_a) at the fundamental period of the structure. The modal shape was analyzed by Ritz vectors method, in which portal sway mode was the most important modes of the container crane. The fundamental period of the crane was around 1.35 s. The ground motions were scaled by increasing its spectral accelerations at the period of 1.35 s to two levels, i.e. 0.2 g and 0.8 g, as shown in Figure 3. Spectral acceleration of 0.2 g used for the case that there is no uplift phenomenon, while S_a of 0.8 g will produce uplifting for all ground motions. This method was also used in Tran et al.'s research [8], the authors scaled ground motions to the design earthquake with a return period of 2400 years for soil type S_D according to design response spectrum in KBC 2016 (S_a = 0.21 g). The detailed steps of this process are presented as following:

1. Compute the spectral acceleration S_{a0} from original response spectral acceleration at the fundamental period of crane T = 1.35 s.
2. Determine the scale factor (α_i) by α_i = target S_a/S_{a0} (in this study, target S_a = 0.2 g and 0.8 g)
3. The horizontal accelerations that were used in the analysis were determined by times original horizontal acceleration with α_i.

The ground motions after scaling are shown in Figure 4.

2.4. Method of Analysis

Time history analysis was used to evaluate the dynamic response of container crane to seismic load. The dynamic equilibrium equation can be expressed as follows [11]:

$$Ku(t) + C\dot{u}(t) + M\ddot{u}(t) = r(t) \qquad (2)$$

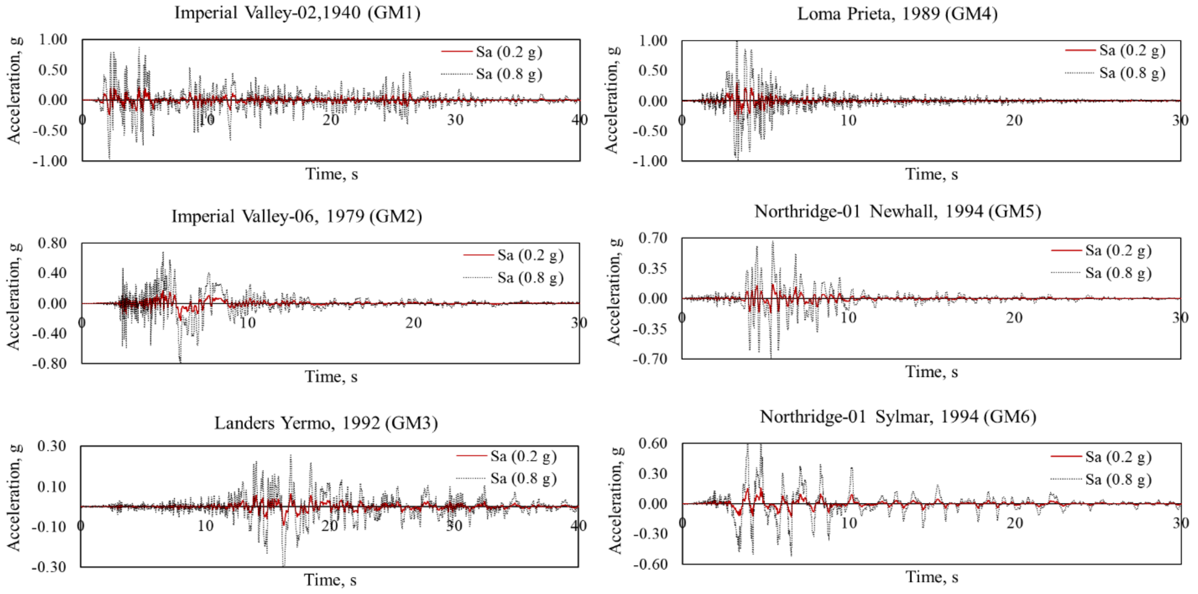

Figure 4. Ground motions

Where K is the stiffness matrix; C is the damping matrix; M is the diagonal mass matrix; while u, u̇ , and ü are the displacements, velocities, and accelerations of the structure; r is the applied load. Equation (2) was solved by direct-integration, nonlinear analysis may be also considered.

In B. D. Kosbab's work [12], the author described the response of container crane when the uplift occurs that the container crane undergoes four stages: firstly, the structure moves seaward due to seismic load; secondly, landside legs translate laterally and uplift due to total gravity load transferred to waterside legs; thirdly, the load increases on waterside legs; finally, landside legs land inside the crane rail, resulting in residual inward displacement of each leg. These Kosbab's analyses are suitable for the real damages of container crane after the Hanshin Awaji Great earthquake in Japan (1995). In the report of The Japan Society of Mechanical Engineers [13], major damage of container crane was bucked at the top of column legs.

In this study, the uplift analysis was considered with the target spectral acceleration $S_a = 0.8$ g, then plastic hinges might happen because the structure behaves in the inelastic state. Thus, the plastic hinges were assigned for the portal beam and legs of the crane to consider these behaviors. Properties of the plastic hinges were assigned with default properties described in ASCE/SEI 41-13 [14].

3. RESULTS AND DISCUSSIONS

3.1. Uplift Response

The uplift behavior was only captured by the Gap element. As mentioned above, the uplift phenomenon happens when the vertical movement of the leg is positive and the vertical force must be equaled to zero. For an example, the result of Imperial Valley-02 (1940) earthquake is shown in Figure 5. As can be seen that the vertical reaction of the landside leg (joint 10) equal to zero at the moment that the vertical movement shows positive value (at the time of about 4.0 s).

The maximum value of the vertical movement is shown in Figure 6. Overall, the uplift response of landside legs (joint 10 and 20) is more than that of the seaside legs (joint 30 and 40), the difference between joint 10 and 20 of landside legs or joint 30 and 40 of seaside legs was not significant. This can be explained by the total gravity load of the container crane located at waterside legs as a result of the effect of boom structure. There were four earthquakes that generated uplifting on both seaside and landside legs. While there were two earthquakes that produced the uplift event only the landside legs (joint 10 and 20). In terms of the spectral acceleration of 0.8 g at fundamental period of container crane, the uplift of landside legs was from 2.7 cm to 13.2. cm in which the minimum value was for the Northridge-01 Sylmar (GM6) earthquake while the maximum value was for Imperial Valley-06 (GM2) earthquake. However, the uplift of the seaside legs was from 2.4. cm to 5.5 cm in which the minimum value was for Imperial Valley-02 earthquake (GM1) while the maximum value was for Landers Yermo (GM3) earthquake).

3.2. Total Base Shear

Figure 7 compared the total base shear of the Pin and Gap boundary conditions when container crane was expected to be uplifted. It means that it is considered for the case $S_a = 0.8$ g. Overall, the total base shear of Pin model was higher than that of the Gap model. The most significant difference was 310 kN for the GM4 (Loma Prieta), in which Pin support was 5534 kN while Gap support was

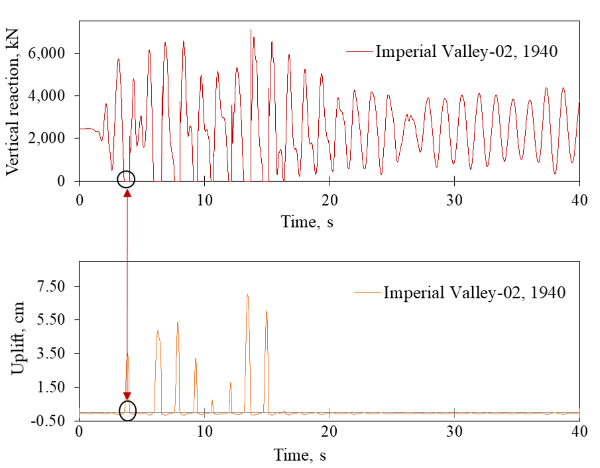

Figure 5. Uplift and reaction of landside leg – Joint 10

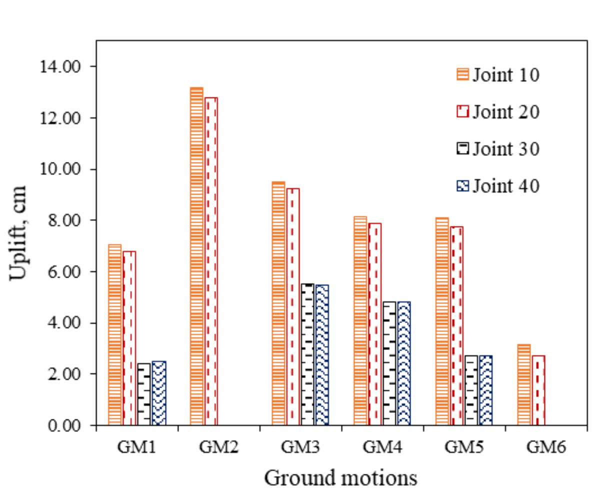

Figure 6. Maximum uplift of Gap model

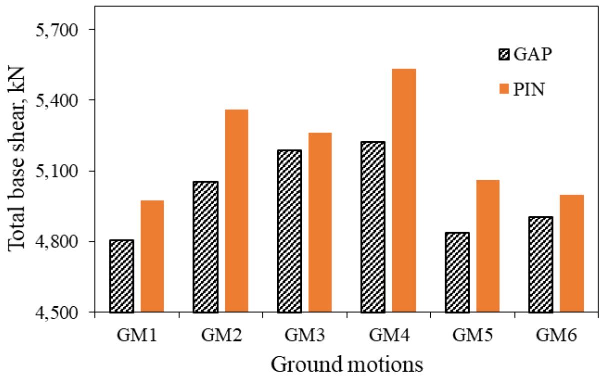

Figure 7. Total base shear (S_a= 0.8 g)

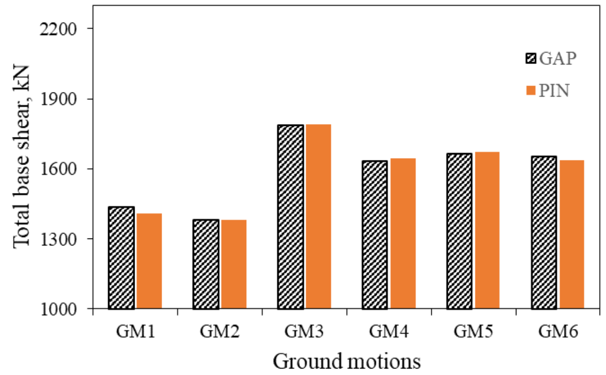

Figure 8. Total base shear (S_a= 0.2 g)

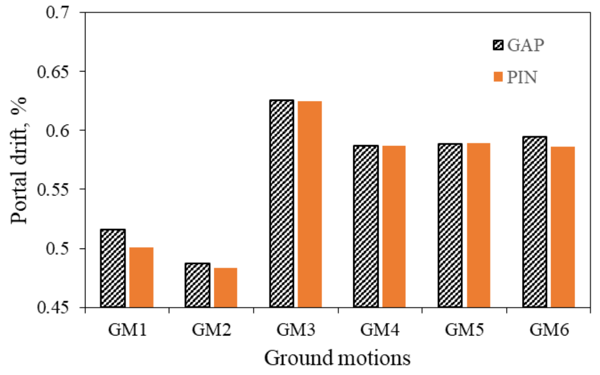

Figure 9. Portal drift (S_a = 0.2 g)

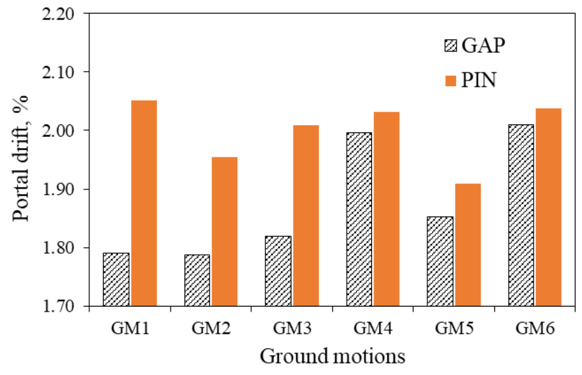

Figure 10. Portal drift (S_a = 0.8 g)

5224 kN. However, For Landers Yermo (GM3) earthquake, the difference was 75 kN, Pin support was 5262 kN and Gap element was 5186 kN.

On the other hand, the total base shear was nearly the same for Gap and Pin supports when the uplift event did not happen. There were no difference between the results of using Pin and Gap element. This means that the boundary conditions of the numerical model do not affect the dynamical response of container crane under low seismic intensity (for example 0.2 g in this study). The average total base shear of six earthquakes for Gap element was 1592 kN, while for Pin support was 1589 kN. The maximum value was about 1787 kN for the Landers (Yermo), while the minimum value was approximately 1380 kN for the Imperial Valley-06, as shown in Figure 8.

3.3. Drift of the Portal Frame

When the spectral acceleration of 0.2 g, there was not a significant difference of portal drift for Pin and Gap support. The average portal drift of six earthquakes for Pin and Gap support was 0.56%. The maximum value was 0.62% for the Landers (Yermo), while the minimum value was 0.48% for the Imperial Valley-06, as shown in Figure 9.

However, the differences need to be noticed when analyzing with the spectral acceleration of 0.8 g. The Figure 10 showed the result of analysis with S_a = 0.8 g. Overall, the portal drift of Pin was larger than that of the Gap. The most differences were 0.26 percent for the Imperial Valley-02, while two earthquakes (Loma Prieta and Northridge-01 Sylmar) had the least deflection about 0.03 percent. The maximum drift of Pin model was 2.05% for Imperial Valley (GM1) earthquake while that of Gap model was 2.01% for Northridge-01 Sylmar (GM6) earthquake. The minimum value of Gap model was 1.79% for two earthquakes (GM1 and GM2). Therefore, the boundary condition of the numerical model of container crane will affect the horizontal movement of portal frame if its dynamical response has uplift event. In this study, the result has showed that the portal drift could be reduced because of uplift.

3.4. Vertical Reaction

Vertical reaction of the leg will change if the uplift event of container crane occurs. Figure 11 shows the effect of uplift on the reaction of legs for Imperial Valley-06. Overall, the magnitude of the vertical reaction of the Gap element was larger than that of the Pin for both landside and seaside legs. At the time of the uplift event, while the vertical reaction of landside leg equaled to zero for the Gap model,

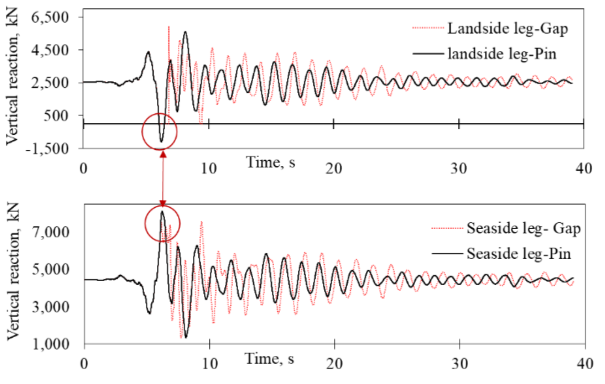

Figure 11. Vertical reaction of Imperial Valley-06, 1979 earthquake (S_a = 0.8 g)

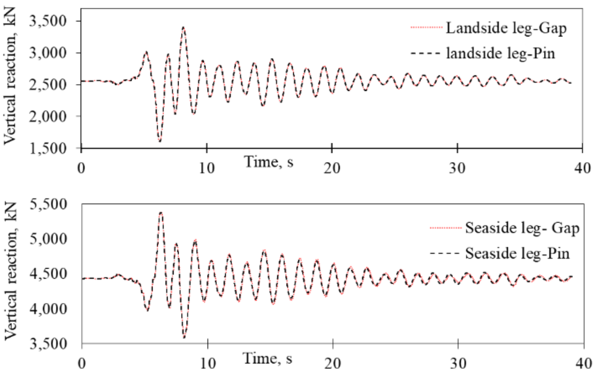

Figure 12. Vertical reaction of Imperial Valley-06, 1979 earthquake (S_a = 0.2 g)

the Pin model still had a negative value. It means that the landside legs of Pin model were subjected a tensile load when uplift happened. Therefore, the Pin model was not suitable for reflecting uplift event because the lifted leg was free in this case. On the other hand, the opposite legs (seaside legs), the vertical reaction of Pin model was higher than that of Gap model. As can be seen from the Figure 11, there was a redistribution of load on the seaside leg of Gap model when uplift happened. It reduced the load by 6.7% as compared to Pin model in this case.

When considering the seaside and landside leg at uplifted time (e.g. Imperial Valley-06), the uplift event happens from 6.1 s to 6.8 s for joint 10 and 20 of the landside leg. It means that the seaside legs (joint 30 and 40) were subjected the total gravity load of the container crane. The legs of the crane will work in the most dangerous condition. It is suitable the fact when the seaside legs often have the hinge before landside legs.

On the other hand, in terms of S_a = 0.2 g (as shown in Figure 12), the figure of Pin and Gap supports were nearly the same for vertical reaction. Therefore, if the dynamical response of container crane does not have any uplifting, there will not be different of the vertical reaction for Pin and Gap model. Figure 12 showed the vertical reaction of Imperial Valley-06 earthquake when S_a = 0.2 g.

4. CONCLUSION

In this study, two boundary condition models of crane were investigated by using SAP2000, and the time histories of six real earthquakes were used for analytical purpose. The input ground motions was divided into two cases. Firstly, the original earthquakes were scaled to the S_a = 0.2 g which expected no uplift event. Secondly, the original earthquakes were scaled up to S_a = 0.8 g which expected that container crane has been uplifted. The results are as follows:

When analyzing the dynamic response of crane under high seismic load, it is necessary to notice the boundary condition of the crane. It means that the link between legs and crane rail need to be simulated accurately. The effect of uplift makes the total base shear reducing. Total base shear of Gap element is less than that of the Pin support when the seismic load is large enough to make the legs lifted. However, the effect of boundary condition can be ignored if the crane does not have uplift phenomenon.

As analyzed above, two seaside legs will be subjected to all weight of container cranes if the uplift happens for two landside legs. The Gap element reflected more accurately than Pin supports. The results also showed that the concentration of load on two seaside legs will be clearer when the Gap model is applied in numerical method.

Portal drift is a crucial value to identify limit state for container crane. In this study, the effect of boundary condition on the portal drift would be significant if the crane occurred uplift. Using Pin support make the portal beam more deformed. It means that the result of Pin support is not accurate in case the crane has been uplifted under seismic load. The Gap element should be considered in the minor uplift that the derailment of the crane legs is ignored or is very slightly.

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