STUDYING SEISMIC DISPLACEMENT OF A CONTAINER CRANE BY SHAKING TABLE TEST AND PUSHOVER ANALYSIS

NGHIÊN CỨU CHUYỂN DỊCH DO ĐỘNG ĐẤT CỦA KẾT CẤU CẨU HÀNG CONTAINER BẰNG THÍ NGHIỆM BÀN RUNG VÀ PHÂN TÍCH ĐẨY DẦN

VAN BAC NGUYEN[a,*]
[a]Faculty of Civil Engineering, VNU Hanoi, University of Engineering and Technology, Hanoi, Vietnam
*Corresponding Author, *E-mail:* bacnguyenvan@vnu.edu.vn
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Abstract: *In this study, the seismic response of a container crane under a ground motion was investigated by using shake table testing on a 1/20 scale container crane. The 1/20 scale container crane was designed and fabricated according to the similitude laws, utilizing three independent quantities such as geometric length, acceleration, and elastic modulus were used to design the 1/20 scale container crane. The Pohang earthquake was used to evaluate the seismic response of the 1/20 scale container crane at the Seismic Research and Test Center, Pusan National University, Yangsan Campus. The results showed that the maximum strain on the seaside leg occurred at the top of the lower seaside leg. The displacement demand on the container crane was accessed, paying particular attention to the portal frame. The container crane exhibited an elastic-range response, with a portal drift of approximately 14.8 mm when the container crane was subjected to the ground motions with the response spectrum matched to the seismic level Z1S4_2400.*

Keywords: *Response spectrum, Acceleration time history, Similitude law, Strain gauges, Portal drift.*

Tóm tắt: *Trong nghiên cứu này, phản ứng địa chấn của một cần cẩu container dưới tác động của chuyển động mặt đất đã được khảo sát bằng cách sử dụng thí nghiệm trên bàn rung với mô hình cần cẩu container tỷ lệ 1/20. Cần cẩu container tỷ lệ 1/20 được thiết kế và chế tạo theo các quy luật tương tự, sử dụng ba đại lượng độc lập như chiều dài hình học, gia tốc và mô đun đàn hồi để thiết kế cần cẩu container tỷ lệ 1/20. Động đất Pohang được sử dụng để đánh giá phản ứng địa chấn của cần cẩu container tỷ lệ 1/20 tại Trung tâm Nghiên cứu và Thử nghiệm Địa chấn, Trường Đại học Quốc gia Pusan, cơ sở Yangsan. Kết quả cho thấy rằng độ biến dạng lớn nhất ở chân biển xảy ra tại đỉnh của chân biển phía dưới. Khả năng dịch chuyển của cần cẩu container đã được đánh giá thông qua vị trí khung cổng. Cần cẩu container phản ứng trong phạm vi đàn hồi, với độ trượt của khung cổng khoảng 14,8 mm khi cần cẩu container chịu tác động của các chuyển động mặt đất với phổ phản ứng phù hợp với mức độ địa chấn Z1S4_2400.*

Từ khóa: *Phổ phản ứng, Lịch sử thời gian gia tốc, Quy luật mô phỏng; Cảm biến biến dạng; Độ trôi cổng.*

1. Introduction

Container cranes are special equipment widely used in seaports to transfer containers between ships and harbors. Despite having an important role in freight, container cranes have been one of the most vulnerable equipment at harbors, as observed in past earthquakes. In past studies by various researchers, buckling and plastic hinge formation in portal frames were identified as typical failure modes under seismic excitation [1–5]. In those studies, however, details on the cause and location of damages have not been clearly presented. Therefore, this study analyzes a container crane located at Gwangyang port in Korea to find the most vulnerable location on the column leg under a seismic excitation by employing shake table testing on a 1/20 scale container crane. In order to accurately reflect the seismic response of the prototype crane, the 1/20 scale crane was designed according to the similitude law [6–9]. This allows for the conversion of the prototype crane into a lab-size scale crane using scaling factors. The seismic responses of container cranes were studied by employing shake table testing on scale crane models in some previous studies. For instance, 1/20 and 1/10 scale models of container cranes were constructed to study the seismic response, including uplift and derailment [1,2,5,10,11]; a 1/50 scale container crane were studied to evaluate the effect of a base isolator on the strain and acceleration amplitude under earthquake loads [9]; Azeloglu et al. [12] used results of shake table testing on 1/20 scale container crane to build a mathematical model for the crane.

Pushover analysis (PA) is a nonlinear static analysis method primarily based on the assumption that a structure's seismic response is governed by its first mode of vibration, or the first few modes, with the shape remaining consistent throughout both the elastic and inelastic stages of response[13]. In PA, a numerical model of the structure is subjected to a lateral load pattern, which helps establish a relationship between the lateral displacement and the lateral load. The load intensity is gradually increased to reach the limits of structural components, such as yielding, plastic hinge formation, and cracking, by pushing the structure into the inelastic stage. The selection of the load pattern is crucial in capturing dynamic phenomena through static analysis, as it can significantly influence the results [14–17]. The PA includes various methods, such as the Capacity Spectrum Method (CSM) and Displacement Coefficient Method (DCM) as adopted by the Applied Technology Council (ATC-40) and Federal Emergency Management Agency (FEMA 356 and 440) [18,19]; Improved Capacity Spectrum Method (ICSM) as proposed by Fajfar [20]; N2 method, as proposed in Eurocode 8 [21]; and Modal Pushover Analysis (MPA) by Chopra and Goel [22]. In this study, DCM in FEMA 356 was used to evaluate the seismic response of a container crane when it was subjected to seismic motion.

2. Scale model design and input motion

2.1 A 1/20 scale container crane

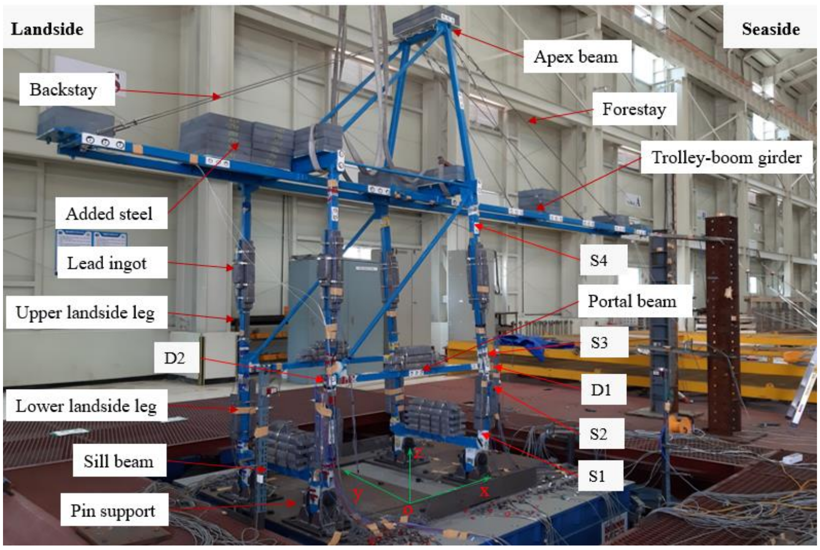
A container crane located at Gwangyang port, Korea was employed to design the 1/20 scale container crane. The basic properties of the prototype crane include: a total height of 78 m from the ground to the top of the crane, a length of trolley boom girder length of 136 m, a portal beam height of 17.5 m, a crane rail span of 30.5 m and a total mass of approximately 1,175 tons from a mass of frame itself (885 tons) and a mass of other components (290 tons). In order to design the 1/20 scale crane model, the scale factors (see Table 1) were calculated based on the similitude law. The cross-sections of each part of the scale crane were designed using the scale factor for the moment of inertia. The scale factors for converting the quantities from the prototype crane to the scale crane were determined by Equation (1).

$$S_l = \frac{L}{l};\ S_E = \frac{E}{e};\ S_a = \frac{A}{a};\ S_m = \frac{M}{m};\ S_t = \frac{T}{t};\ S_I = \frac{I}{i} \quad (1)$$

where S_l; S_E; S_a; S_m; S_t; S_I are the scale factors of geometric dimension, elastic, acceleration, mass, time, and moment of inertia, respectively. It should be noted that the uppercases in Equation (1) describe the quantities of the prototype crane, while lowercases indicate the quantities of the scale crane.

Table 1. *Scale factors for designing the 1/20 scale crane*

Quantities	Symbol	Scale factor	Quantities	Symbol	Scale factor
Geometric length, l	S_l	20	Mass, m	S_m	400
Elastic modulus, E	S_E	1	Time, t	S_t	4.472
Acceleration, a	S_a	1	Moment of inertia, I	S_I	160,000



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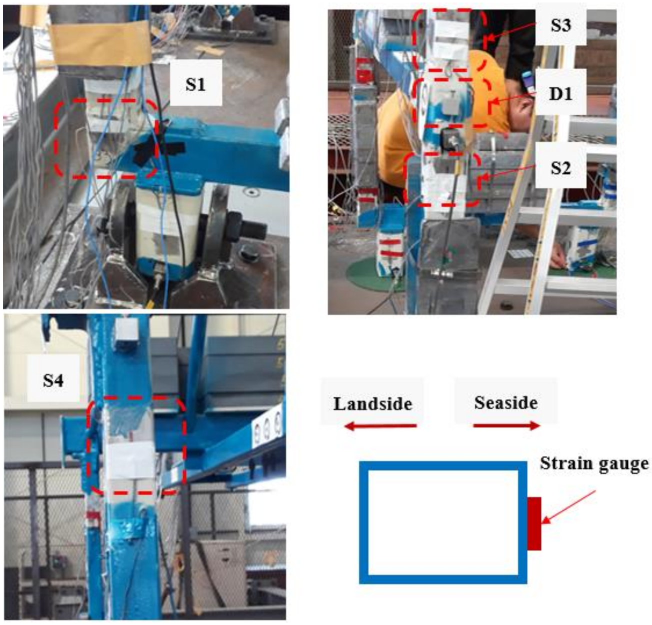

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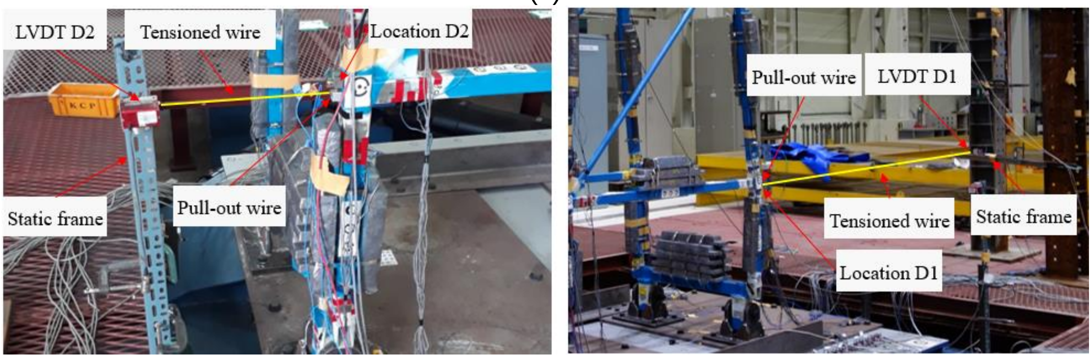


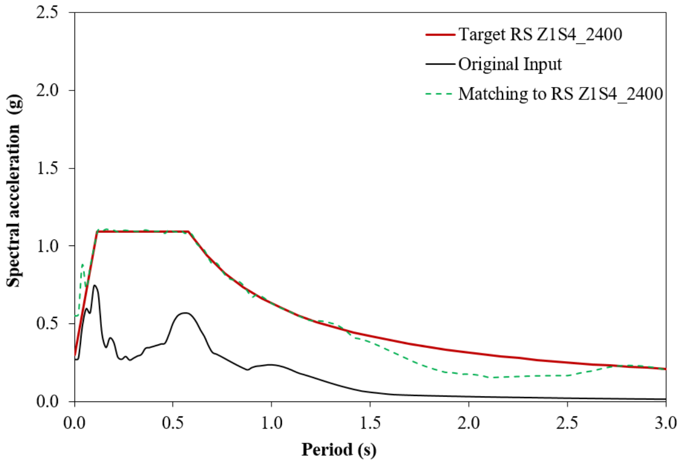
(c)

Fig. 1. *(a) The 1/20 scale container crane; (b) Installing strain gauge; (c) Installing LVDT*

The 1/20 scale crane is shown in Fig. 1. The total converted mass of the scale crane was 2,939 kg. After down-scaling the cross-section of the prototype crane, the self-frame mass of the scale crane was only 235.5 kg, thus requiring the introduction of additional mass to the scale crane [23]. An additional mass of 2703.5 kg was attached to the scale crane in two ways: by using steel bars, which were attached to the trolley boom girders and the apex beam by weldings and bolts and lead ingots, which were attached to the upper landside and seaside legs, the lower landside and seaside legs, portal beams, and sill beams by using steel ties. The boundary condition model for the scale container crane was pin support, which allows crane leg rotation but not movement in both horizontal and vertical directions. Strain along the seaside leg was determined via strain gauges that were attached to frames to find the most stressed location: location S1 was the bottom of the lower seaside leg; location S2 was the top of the lower seaside leg; location S3 was the bottom of the upper seaside leg; and location S4 was the top of the upper seaside leg. The drift of the container crane was determined at the end of the portal beam at the seaside and landside (D1 and D2, respectively) using a linear variable differential transformer (LVDT). The measured locations are shown in Fig. 1.

2.2 Input ground motion

For this study, the input ground motion was the 2017 Pohang earthquake, which has a magnitude of 5.4 on the Richer scale and a peak ground acceleration of 0.27g. To characterize the elastic Korean design standard [24,25], the response spectrum of the ground motion was matched to the elastic response spectrum RS Z1S4_2400 [26,27]. The response spectrum was developed with the following parameters: seismic zone 1, soil type S4 (deep and hard ground), and a return period of 2400 years, as depicted in the Korean design standard [24,25]. Then, the adjusted acceleration time history was scaled down by the scale factor for time (S_t = 4.472) and acceleration (S_a =1) to create the input ground motion of the shake table testing. Fig. 2 (a) shows the original and matched response spectra of the Pohang earthquake and the target response spectrum (RS Z1S4_2400); Fig. 2 (b) and (c) show the original and matched acceleration time histories, respectively; Fig. 2 (d) shows the input for shaking table test. The earthquake was applied on the scale crane along the trolley boom direction to determine its seismic responses.



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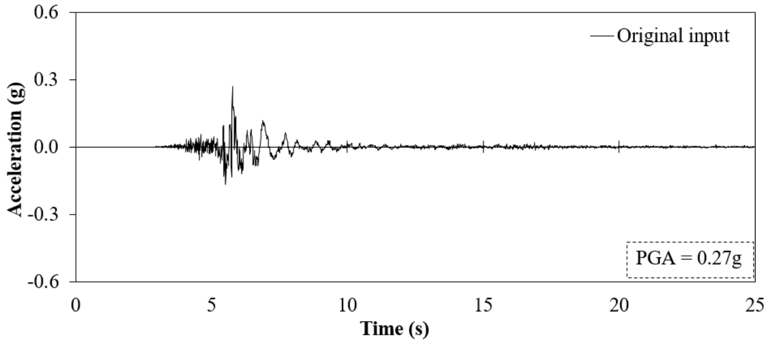

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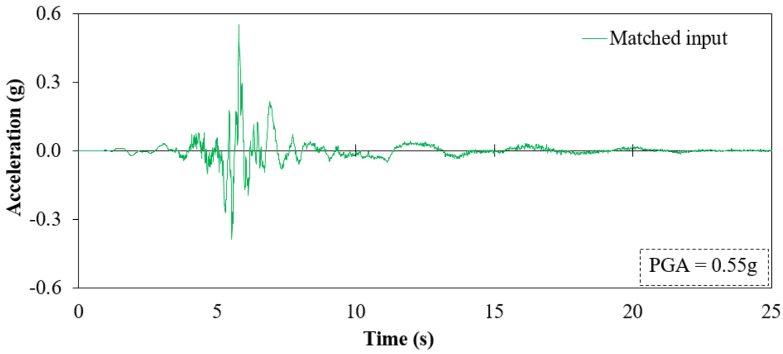

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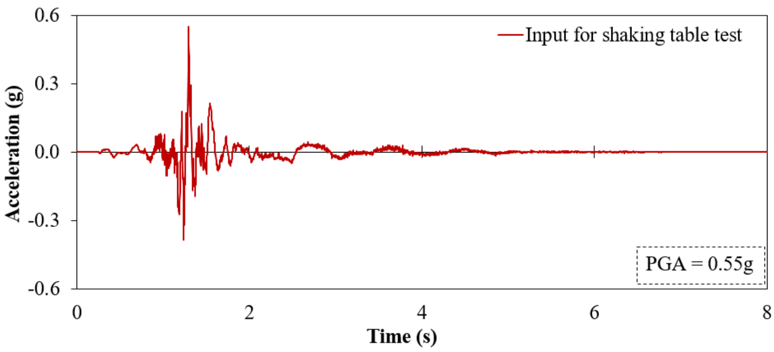

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Fig. 2. *Input ground motions: (a) response spectrum; (b) original acceleration time history; (c) matched acceleration time history; (d) acceleration time history for shaking table test*

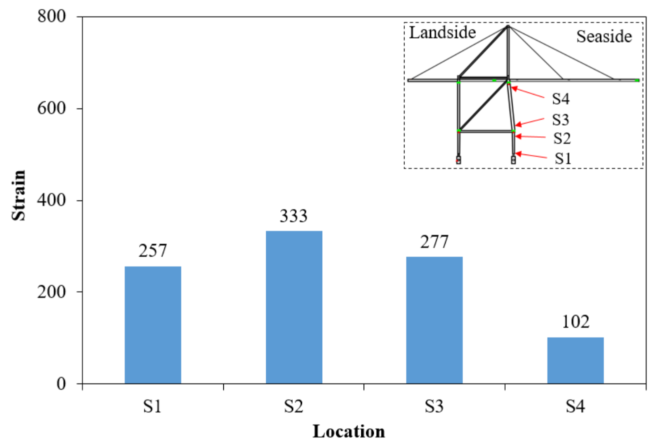
3. Results and Discussions

Performance-based design is an emerging structure methodology developed from the lessons learned in the 1990s earthquakes [28–30]. It enables building owners to define performance levels, such as collapse prevention, life safety, damage control, and continued operation. Traditional seismic design focuses on providing the capacity to withstand a predefined seismic force but does not address how a structure will perform if the forces exceed the design limit. Construction or retrofitting costs may become excessively high if the design is based on rare, high-intensity seismic events. Conversely, predicting a structure's performance under stronger ground motions becomes difficult if the design is based on more frequent seismic events. The performance level of a container crane focuses on minimizing downtime caused by structural damage during seismic events. To assess this, limit states can be defined based on expected downtime, which can be linked to specific repair strategies tied to varying levels of structural damage. These damage levels are quantified using a chosen global engineering demand parameter (EDP). The portal deformation is used as the EDP to assess damage levels, which correspond to different repair methods and the associated downtime required for repairs. Table 2 shows the performance levels, damage levels, and repair downtimes.

Table 2. *Performance level and their expected downtimes [31]*

Performance level	Whole structures	Portal beam	Overall damage	Mean (days)
Derailment	Derailment without any structural damage	Elastic	Derailment	6
Immediate use	Minor structural damage; Derailment occur or not occur	Low limit: elastic. High limit: some minor buckling of hollow sections	Minor damage	10
Structural damage	Extensive damage and will not be suitable for use without major repairs, but not collapse	A portal deformation is lower than deformation at maximum load capacity up to the point of ultimate ductility	Major damage	60
Complete collapse	Local buckling near the portal frame can quickly lead to global instability and eventual collapse	Portal deformation surpasses the estimated point of maximum ductility	Collapse	330

3.1 Strain of the seaside leg



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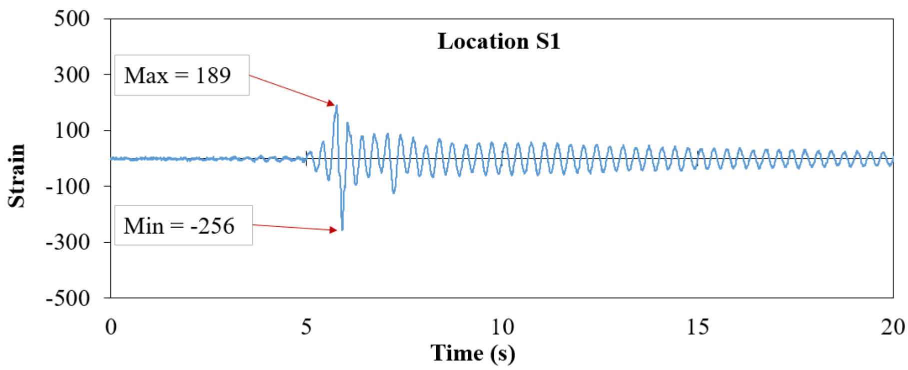


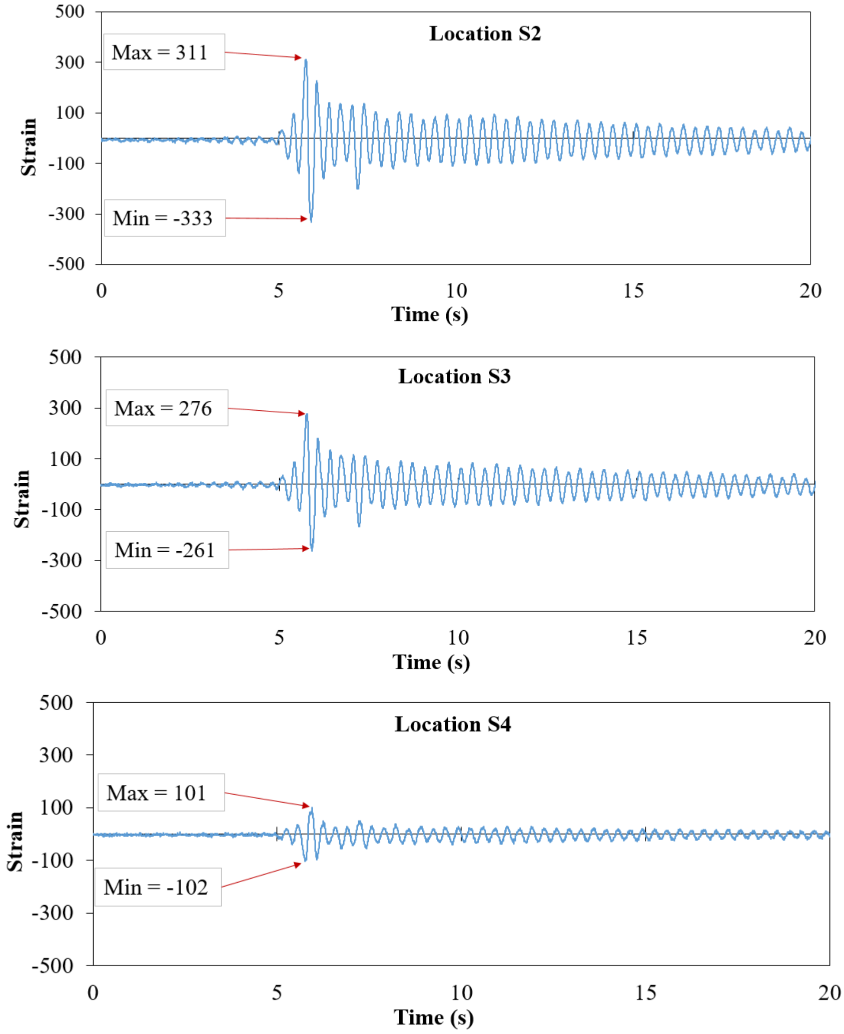
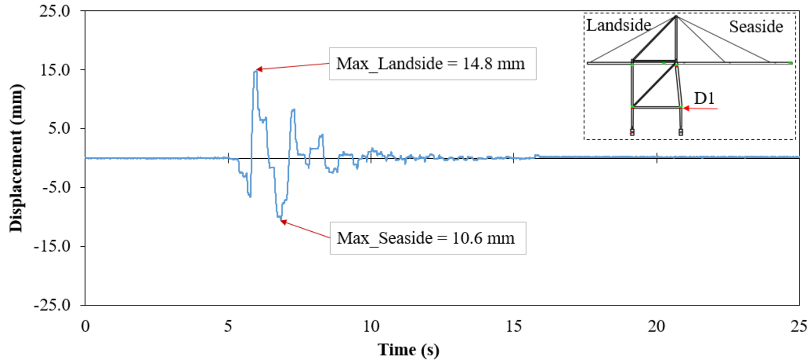


Fig. 3. *Strain of the seaside leg*

The strain of the seaside leg was determined via four strain gauges. The maximum strain observed at locations S2 and S3 were 333 and 277 (micro-strain), respectively. It means that the leg will occurs a plastic hinge at the location S2 or S3. Unlike buildings, where roof displacement is often the focus, container crane dynamic analysis typically examines the horizontal displacement or drift at the top of the portal frame. This is because the drift reflects the deformation in the portal frame, which is the main structural element supporting the upper parts of the crane. Historical earthquake data shows that plastic hinges tend to form at the portal frame legs, making portal deformation a key seismic response [4]. Thus, the results obtained in the shaking table test on the 1/20 scale container crane also reflected the previous studies and recorded incidents occurring in reality.

3.2 Portal drift



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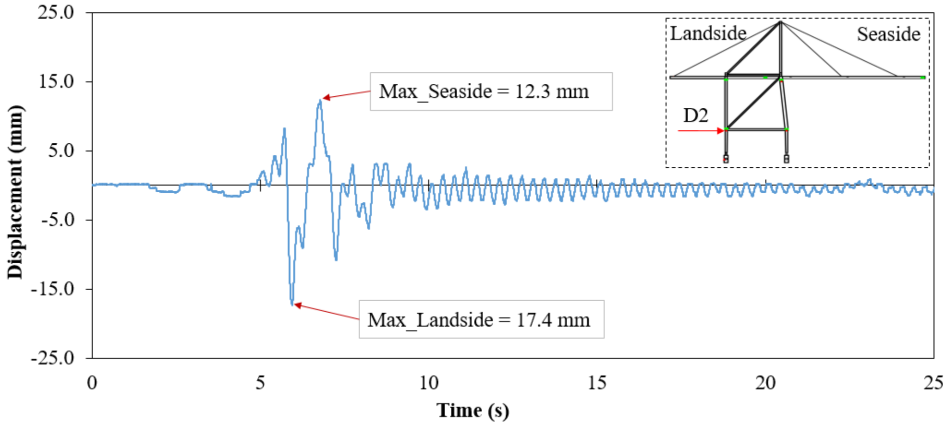
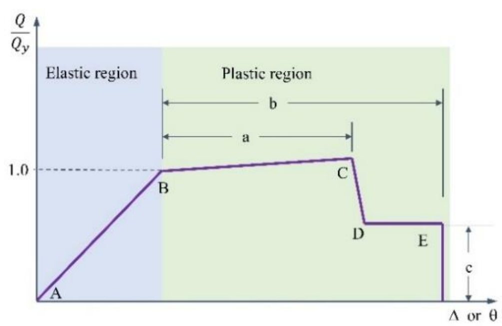


(b)

Fig. 4. *Portal drift*

The portal drift of the 1/20 scale container crane was measured at locations D1 and D2, which correspond to the end of the portal beam at the seaside and landside, respectively. The LVDT D1 and D2 were attached to the static frame on the ground while the pull-out wires were attached to the location D1 and D2 of the portal beam at the landside and seaside, as shown in Fig. 1 (c). Under the Pohang earthquake, with the response spectrum matched to the elastic response spectrum RS Z1S4_2400, the maximum portal drift at the seaside and landside were 14.8 mm and 17.4 mm, respectively. At position D1, the maximum displacement towards the landside and seaside are 14.8 mm and 10.6 mm, respectively. In position D2, the maximum displacement towards the landside and seaside are 17.4 mm and 12.3 mm, respectively.

The pushover curve of the scale container crane was determined by finite element analysis to evaluate the working stage of the container crane under the seismic level. The pushover curve is a plot of the base shear force versus portal drift (location D1 at portal beam), as depicted in Fig. 5 (c). To simulate the material nonlinear behaviour of the steel used for the member sections, plastic hinges were introduced at specified locations close to the beam-column joints in the portal frame. The behaviour of the plastic hinges assigned to the portal frame and column legs was defined based on FEMA 356 [18] and the American Society of Civil Engineering (ASCE/SEI 41-13) [32]. The linear elastic response is depicted between point A (unloaded component) and an effective yield point B. C has an ordinate that represents the strength of the component and an abscissa value equal to the deformation at which significant strength degradation begins (line CD). Beyond point D, the component responds with substantially reduced strength to point E. At deformations greater than point E, the component strength is essentially zero. The idealized behaviour of steel via the plastic hinge is depicted in Fig. 5 (a). The plastic hinges (yielding) first occur at the top of the lower seaside legs for the 1/20 scale container crane. At this yielding point, the portal drift of 37.5 mm was recorded for a push force of 26.4 kN (see Fig. 5 (b) and (c)). Therefore, with the portal drift response of approximately 14.8 mm under the seismic level Z1S4_2400, the 1/20 container crane was observed to respond within the elastic region.



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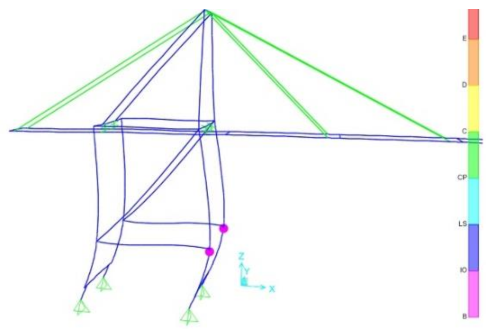

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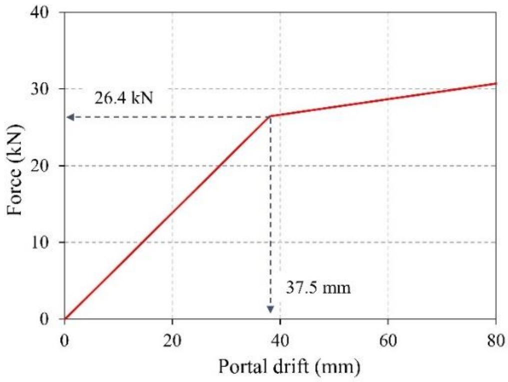

(c)

Fig. 5. *Building a pushover curve for scale crane: (a) stages of the plastic hinge; (b) deformed shape of portal frame; (c) pushover curve*

4. Conclusions

The seismic response of the container crane was evaluated by employing shake table testing of its 1/20 scale crane. The scale crane was designed based on similitude law, where the cross-section of each part was scaled down by using the scale factor of the moment of inertia, and artificial masses were used to satisfy the total mass of the scale crane. The ground motions were matched to the elastic response spectrum (RS Z1S4_2400) and applied to the scale crane along the trolley-boom girder direction. Major findings obtained from this study are summarized as follows:

The results indicated that the maximum strain on the seaside leg occurred at the top of the lower leg. The maximum strain at the top of the lower seaside leg and the bottom of the upper seaside leg were 333 and 277 (micro-strain) under the earthquake with response spectrum matched to the elastic RS Z1S4_2400. Therefore, the location around the portal frame, especially the top of the lower seaside leg, was the most stressed part of the container crane.

The portal drift of the scale crane was determined under the action of the seismic excitations. The results indicated that the 1/20 scale container crane works in the elastic stage under the ground motions (Pohang earthquake) with the response spectrum matched to the design response spectrum Z1S4_2400. The portal drift was recorded as 14.8 mm and 17.4 mm for the end of portal frame at the seaside and landside, respectively.

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