

# Real-time estimation of responses and loads of real-scale pipes subjected to earthquakes and external loads using digital twin technology

Dongchang Kim<sup>1a</sup>, Shinyoung Kwag<sup>\*\*2</sup>, Sung-Jin Chang<sup>3b</sup> and Seunghyun Eem<sup>\*1</sup>

<sup>1</sup> School of Convergence & Fusion System Engineering, Kyungpook National University, 80 Daehak-ro, Daegu, 41566, Republic of Korea

<sup>2</sup> Department of Civil and Environmental Engineering, Hanbat National University, 125 Dongseo-daero, Daejeon, 34158, Republic of Korea

<sup>3</sup> Seismic Research and Test Center, Pusan National University, 49 Busandaehak-ro, Yangsan, 50612, Republic of Korea

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**Abstract.** Infrastructure facilities contain various pipe systems, which can be considerably damaged by external loads such as earthquakes. Therefore, structural health monitoring (SHM) and safety assessment of pipes are crucial. Digital twin technology for SHM of pipes is important in the industry. This study proposes a digital twin system that estimates the behavior, stress, and external load of real-scale pipes in real time under simultaneous seismic and external loads using a minimum number of sensors. Vibration tests were performed to construct the digital twin system, and a numerical model was developed that considered the dynamic characteristics of a target pipe. Moreover, a reduced-order modeling technique of a numerical model was applied to enhance its real-time performance. The digital twin system successfully estimated the response of the pipe at all points. Verification of the digital twin system was performed by comparing it with the experimental parameters of a real-scale pipe. The proposed digital twin system can help enhance SHM and system's maintenance.

**Keywords:** digital twin; pipe system; real time; reduced-order modeling; structural health monitoring

## 1. Introduction

Pipe plays a critical role as a component of social infrastructure facilities and is exposed to various external loads such as earthquakes (Semke *et al.* 2006, Wiggert *et al.* 1987, Gim *et al.* 2021). Instances of pipe damage caused by earthquakes have occurred, such as the 1994 Northridge earthquake in California, where many pipes ruptured, causing oil leaks and a large fire (O'Rourke *et al.* 1998). Additionally, the 2011 Tohoku earthquake in Japan caused damage to oil and gas pipelines, resulting in leaks and fires (Wakamatsu *et al.* 2016). Thus, damage to pipes caused by seismic loads can compromise the safety of facilities and lead to significant accidents, which can potentially result in loss of life (Fleming and Lydell 2004, Rossi *et al.* 2022, Khan and Abbasi 1999, Teixeira *et al.* 2008, Cai *et al.* 2017). To prevent accidents in pipes, regular inspections and maintenance are necessary. Therefore, structural health monitoring (SHM) and safety assessments are considered important, and various studies have been conducted (Li *et al.* 2022, Gattulli *et al.* 2022). Information on pipe responses measured by sensors is required for effective SHM (Souza *et al.* 2023). The information extracted from

the responses can be used to evaluate the condition of pipe systems and mitigate risks of accidents and malfunctions.

When pipes are subjected to loads, the use of multiple sensors to obtain responses may not be a cost-effective measure, and achieving precise measurements can be challenging because of spatial constraints that arise from the location and shape of the pipe (Uhl and Petko 2022). Pipes are susceptible to data distortion due to noise and external factors that can arise depending on the environmental conditions and rotating machinery such as pumps and motors. Furthermore, estimating the responses of pipes can be challenging because of the diverse types and magnitudes of loads, including seismic events, rainfall, wind, and direct impacts, which are difficult to measure directly (Cruz and Krausmann 2008, Kawsar *et al.* 2015, Wu *et al.* 2015, Eie 2018, Law *et al.* 2005, Arrayago *et al.* 2022, Karlsson 1996).

In response, digital twin technology has emerged as a solution to estimate system responses by utilizing inverse estimation techniques (Oh *et al.* 2020, 2023a, b). Digital twin technology creates virtual environments that replicate all systems in the real world, allowing for monitoring and prediction of the behavior and status of real systems through simulation (Zipper *et al.* 2018, Phanden *et al.* 2021, Madni *et al.* 2021). Systems incorporating digital twin technology exhibit prompt fault detection capabilities, enabled by their ability to conduct various experiments unbound by physical limitations. As a result, not only is the time significantly minimized, but it also reduces the costs associated with physical testing methods (Jones *et al.* 2020, Khajavi *et al.* 2019, Wright and Davidson 2020). Recently, active research has been conducted that utilize digital twin

\*Corresponding author, Ph.D., Professor,  
E-mail: eemsh@knu.ac.kr

\*\*Co-corresponding author, Ph.D., Professor,  
E-mail: skwag@hanbat.ac.kr

<sup>a</sup> Ph.D. Student

<sup>b</sup> Ph.D.

technology to evaluate systems under a single load (Oh *et al.* 2021, 2022, Lin *et al.* 2021, 2023). Research is also being conducted on digital twin systems that estimate responses when fluid structures interact (Oh *et al.* 2023a, b). However, systems are subjected to multiple loads, such as wind loads, vibrations, and earthquakes, depending on environmental conditions (Martin *et al.* 2019, Duthinh and Simiu 2010). Therefore, research on the SHM of systems subjected to multiple loads using the digital twin technology is needed.

This study proposes a digital twin system that estimates real-time loads and acceleration, velocity, displacement, and stress at all points (including unmeasured points) of a real-scale pipe that is subjected to simultaneous seismic and external loads. A digital twin system can estimate the response of all points in the system in the digital world based on the response of some sensors attached to the structure. The digital twin system was applied to a piping system used in nuclear power plants and validated by comparing the response of the pipe in real time. The digital twin system can be used in SHM and safety evaluation by estimating the response of pipes subjected to multiple loads in real time. The digital twin system can also continuously track the structure's condition and provide an opportunity to detect and prevent potential problems early. Therefore, the proposed digital twin system can play an important role in increasing the safety of structures.

## 2. Digital twin system of the pipe

### 2.1 Overview of a digital twin system

The developed digital twin system estimates the response of a pipe to external loads and all points in real time by considering the seismic and external loads that simultaneously act on the pipe. To construct a digital twin system, a numerical model capable of representing the behavior of the pipe was developed, and a reduction technique was applied (Reduced Order Model (ROM)) to obtain real-time computational capabilities. The Newmark- $\beta$  numerical-analysis method was utilized to estimate the pipe response in the digital twin system. The Newmark- $\beta$  method was configured to calculate the displacement, velocity, and acceleration by inputting loads (Newmark 1959). To assess the external load that acted on the pipe, measured ground-acceleration data were used to estimate

the seismic response. Additionally, the responses (displacements, velocities, and accelerations) of a point in the pipe subjected to multiple loads are required. A regularization technique was applied to acceleration data to estimate displacement (Lee *et al.* 2010, Hong *et al.* 2013). Subsequently, velocity was calculated by differentiating the estimated displacement. Then, the external load was calculated through the difference between the estimated seismic response and the response of a point in the pipe subjected multiple loads (Kim *et al.* 2023). The response at all points of the pipe was estimated by applying the estimated external load and seismic-acceleration data to the digital twin system. Fig. 1 shows the overview of digital twin system.

### 2.2 External load estimation formula (Kim *et al.* 2023)

Information about external loads is required to estimate the response of all points in the pipe. The external loads were calculated using the equations of motion.

$$\begin{pmatrix} M^m & M^c \\ [M^c]^T & M^{um} \end{pmatrix} \begin{pmatrix} \ddot{u}^m \\ \ddot{u}^{um} \end{pmatrix} + \begin{pmatrix} C^m & C^c \\ [C^c]^T & C^{um} \end{pmatrix} \begin{pmatrix} \dot{u}^m \\ \dot{u}^{um} \end{pmatrix} + \begin{pmatrix} K^m & K^c \\ [K^c]^T & K^{um} \end{pmatrix} \begin{pmatrix} u^m \\ u^{um} \end{pmatrix} = \begin{pmatrix} f_g^m \\ f_g^{um} \end{pmatrix} + \begin{pmatrix} f_s^m \\ 0 \end{pmatrix} \quad (1)$$

where superscripts  $m$ ,  $c$ , and  $um$  represent the points where the external loads are applied (corresponding to the positions of the sensors), coupling points, and unmeasured points, respectively.  $f_s$  and  $f_g$  represent the external and seismic loads, respectively. To estimate the response at the unmeasured points, Eq. (1) is solved and rearranged into Eq. (2).

$$M^{um}\ddot{u}^{um} + C^{um}\dot{u}^{um} + K^{um}u^{um} = f_g^{um} - ([M^c]^T\ddot{u}^m + [C^c]^T\dot{u}^m + [K^c]^T u^m) \quad (2)$$

After estimating the response at the points other than the measurement point using Eq. (2), the external load that acts on the pipe, i.e.,  $f_s^m$ , can be obtained by expanding the first row of Eq. (1)

$$f_s^m = M^m\ddot{u}^m + C^m\dot{u}^m + K^m u^m + M^c\ddot{u}^{um} + C^c\dot{u}^{um} + K^c u^{um} - f_g^m \quad (3)$$

$$f^m = f_g^m + f_s^m \quad (4)$$

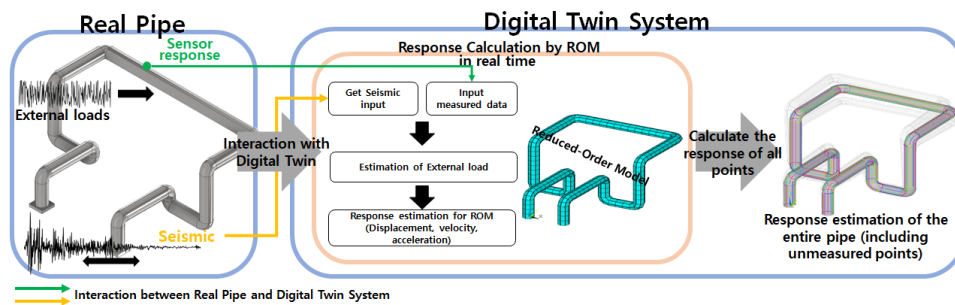


Fig. 1 Overview of the digital twin system

In Eq. (4),  $f^m$ , represents the total load acting on the pipe. Therefore, the external load can be estimated from some responses using the above equation.

### 2.3 Target pipe

Target pipe refers to the piping system used in the Korean Standard Nuclear Power Plant (OPR-1000), which consists of ASME CLASS1 SA312 GRADE TP316 SCH 160 stainless steel pipes with diameters of 0.0603 m and 0.0889 m straight pipe, elbow, reducer, and support (Kwag *et al.* 2020). The different-diameter pipes were connected by welding. Target pipe is used as a connection pipe in case of an emergency stop of the main pipe system of the steam turbine. Target pipe was part of a critical system during seismic and external loading conditions. This pipe was installed on the second floor of a containment building with a height of ~31–35 m. The dotted line in Fig. 2 shows the pipe system installed in the OPR-1000 section.

The target pipe length, width, and height were 0.764, 17.955, and 1.6 m, respectively. A jig was installed at the end of the pipe to facilitate shaking-table experiments. The pipe design is shown in Fig. 3, and the cross-sectional

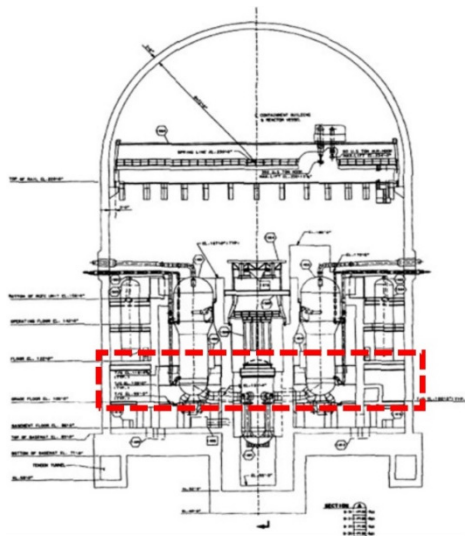


Fig. 2 OPR-1000 containment building section (Gim *et al.* 2021)

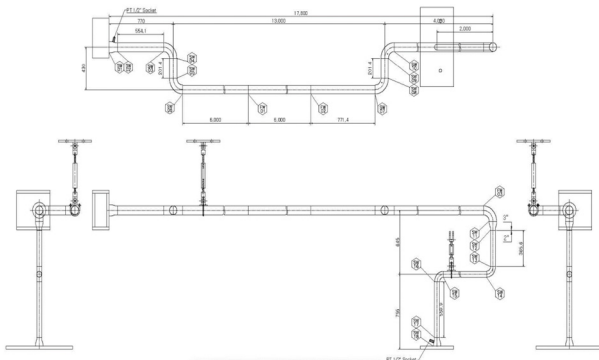


Fig. 3 Specimen drawing of the target pipe (unit: mm) (Gim *et al.* 2021, Kwag *et al.* 2020)

Table 1 Eigenvalue analysis using APDL

Nominal pipe size	Outside diameter	Inside diameter	Thickness
0.0508 m (2 in)	0.0603 m	0.0428 m	0.00874 m
0.0762 m (3 in)	0.0889 m	0.0666 m	0.01113 m



Fig. 4 Experimental setup (Kwag *et al.* 2021)

information of the pipe is listed in Table 1. The pipe was installed on the shaking table, as shown in Fig. 4.

### 2.4 Numerical model of the pipe

A numerical model that can accurately simulate the behavior of a pipe is essential in a digital twin system to achieve high reliability. A random vibration with frequencies that range from 1 to 50 Hz was applied to the shaking table to investigate the resonant frequencies of the actual pipe and verify its dynamic characteristics (Gim *et al.* 2021). Based on this, a numerical model of the pipe was constructed using ANSYS Mechanical APDL, as shown in Fig. 5. The material-property values of the pipe were set as follows: the elastic modulus, density of stainless steel, density of water, and Poisson’s ratio were  $199 \times 10^9$  N/m<sup>2</sup>, 7,954 kg/m<sup>3</sup>, 1,000 kg/m<sup>3</sup>, and 0.3, respectively. The water inside the pipe was considered as an additional mass. The mode shape of the numerical model is shown in Fig. 6. Table 2 lists the natural frequencies of the significant modes in the vertical direction of the numerical model and actual pipe.

The digital twin system of the pipe requires real-time estimation of the pipe behavior, stress, and external loads. However, the constructed numerical model had many degrees of freedom (DOFs), which significantly affected the computational speed and made real-time estimation impossible (Han 2020, Persson *et al.* 2016). Therefore, a model was constructed using the Craig–Bampton reduction



Fig. 5 Numerical model of the pipe

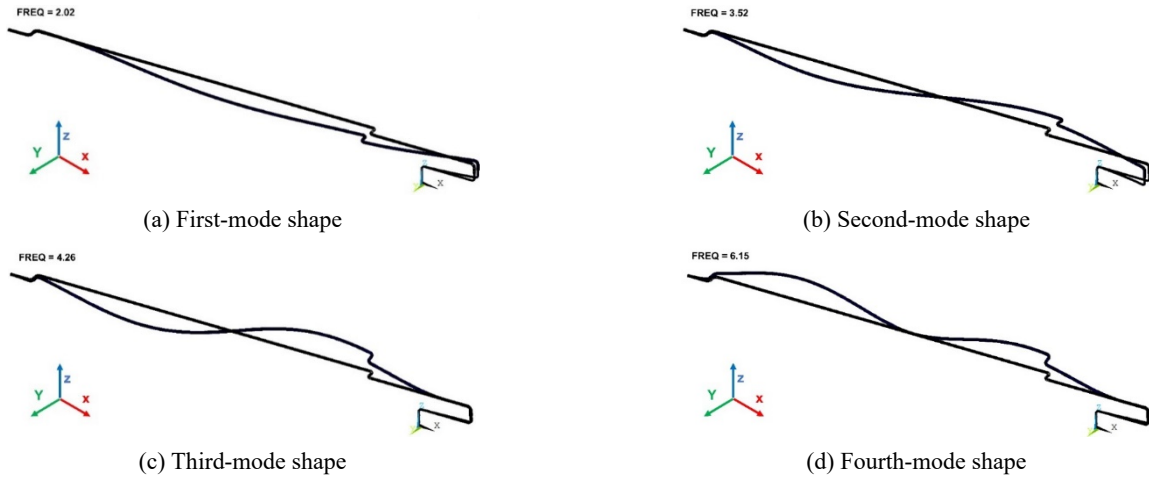


Fig. 6 Mode shapes of the numerical model

Table 2 Comparison of the natural frequency of the pipe through experiment and analysis

	Analysis	Experiment
Model1	2.0 Hz	2.0 Hz
Mode 5	7.2 Hz	7.6 Hz
Mode 7	14.1 Hz	14.2 Hz
Mode 11	25.7 Hz	23.2 Hz

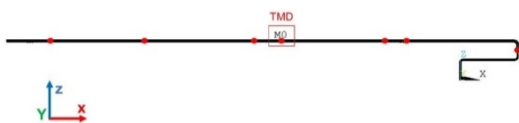


Fig. 7 Nodes used in the reduced-order model of the pipe

modeling technique to enable real-time computation (Criag and Bampton 1968). The reduced-order pipe model was developed with 92 DOFs having 50 mode shapes and 7 nodes among 3,732 DOFs. Fig. 7 shows the nodes used in the reduced-order pipe model.

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estimation of the pipe behavior, stress, and external loads. However, the constructed numerical model had many degrees of freedom (DOFs), which significantly affected the computational speed and made real-time estimation impossible (Han 2020, Persson *et al.* 2016). Therefore, a model was constructed using the Craig–Bampton reduction modeling technique to enable real-time computation (Criag and Bampton 1968). The reduced-order pipe model was developed with 92 DOFs having 50 mode shapes and 7 nodes among 3,732 DOFs. Fig. 7 shows the nodes used in the reduced-order pipe model.

### 3. Vibration experiments of the digital twin system

#### 3.1 Experimental setup and seismic load

Three shaking tables were used to input the seismic load to the target pipe. The shaking table, which consisted of two 3-DOF and one 6-DOF shaking table, was connected, as shown in Fig. 8. Table 3 lists the standards and specifications of the shaking tables.

The target pipe was installed at a height of 31–35 m in a containment building and thus required consideration of the

Table 3 Comparison of the natural frequency of the pipe through experiment and analysis

Item	Performance		
	3 DOFs	3 DOFs	6 DOFs
Max. loading (kg)	30,000	60,000	30,000
Table size (m)	5.0 × 5.0	5.0 × 5.0	4.0 × 4.0
Control axes	3 DOFs (2 translational axes and 1 rotational axis)	6 DOFs (3 translational axes and 3 rotational axes)	6 DOFs (3 translational axes and 3 rotational axes)
Max. displacement (mm)	Hor. (X) = ± 300, Hor. (Y) = ± 200		Hor. (X) = ± 300, Hor. (Y) = ± 200, Ver. (Z) = ± 150
Max. velocity (m/s)	Hor. (X, Y) = 1.0		Hor. (X, Y) = 1.5, Ver. (Z) = 1.0
Max. acceleration (g) at a full table	±1.0	±1.25	Hor. (X, Y) = 1.5, Ver. (Z) = 1.0
Frequency range (Hz)	0.1–60.0		

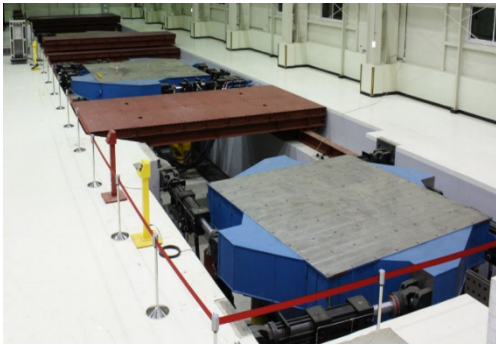


Fig. 8 Shaking tables (Kim and Jeong 2017)

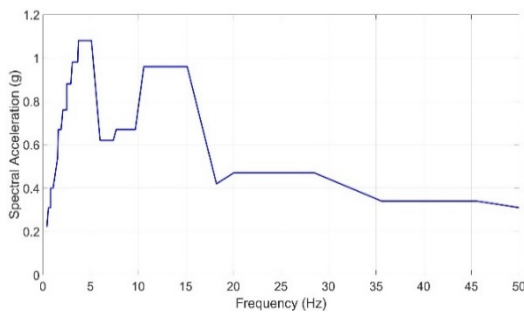


Fig. 9 5%-damping USNRC FRS (Gim *et al.* 2021)

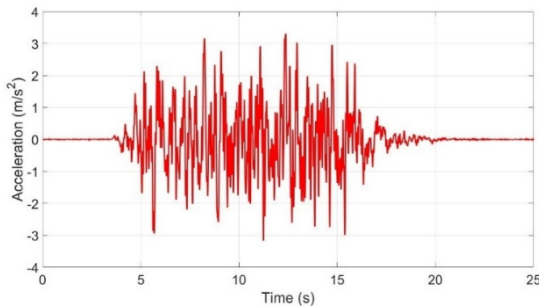
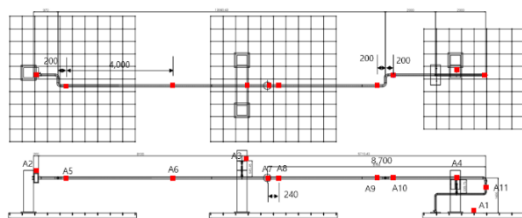
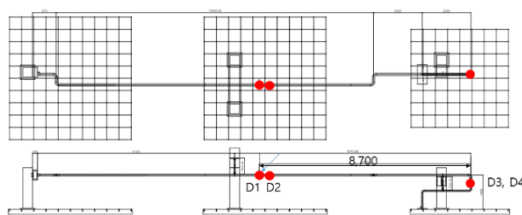


Fig. 10 Input acceleration in the shaking table (Y-axis)



(a) Location of the accelerometer



(b) Location of the linear variable differential transformer

Fig. 11 Location of the sensor (Gim *et al.* 2021, Kwag *et al.* 2021)

amplified seismic forces during an earthquake. The shaking table applied an artificial seismic wave (USNRC FRS) that covered the floor response spectrum (FRS) based on USNRC Regulatory Guide (RG) 1.60 Design Ground

Response Spectrum (Regulatory Guide 1.60 2014). Fig. 9 shows the shape of USNRC FRS. Fig. 10 shows the time-series artificial seismic-wave shape measured on the shaking table. The behavior of the pipe under seismic load, acceleration, and displacement was measured at the location shown in Fig. 11.

### 3.2 External load acting on the pipe

The vibration experiments on the target pipe were performed with and without a tuned mass damper (TMD), as shown in Fig. 12. A TMD with a mass of 16 kg was installed at A7 and D1 based on the acceleration and displacement sensors shown in Fig. 11. Fig. 13 shows the TMD used in the experiment, which reduced the vibration of the pipe during an earthquake. The displacement values obtained from the vibration experiments of the pipe with and without the TMD are shown in Fig. 14, which shows that the TMD affected the response of the pipe during an earthquake. In this study, the effect of the TMD on the pipe was considered as an external load.



(a) Side view without TMD



(b) Side view with TMD

Fig. 12 Experimental setup (Gim *et al.* 2021)

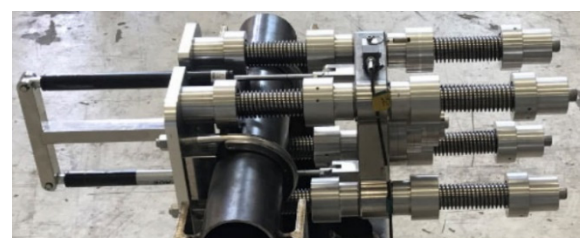
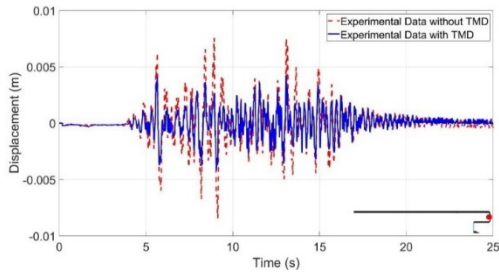
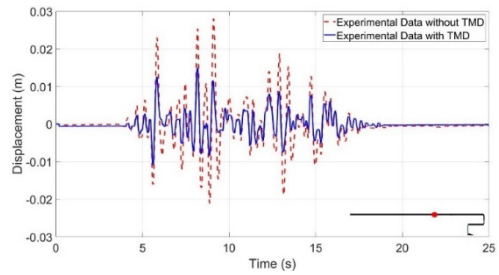


Fig. 13 Drawing of test TMD (Kwag *et al.* 2021)



(a) Y-axis response



(b) Y-axis response

Fig. 14 Experimental data depending on whether or not the TMD was used (Gim *et al.* 2021, Kwag *et al.* 2021)

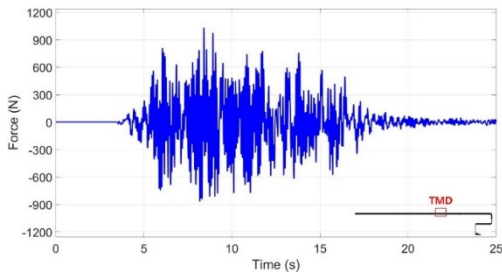
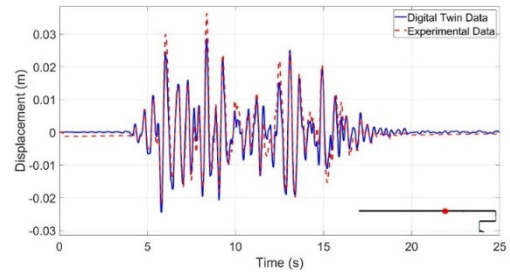


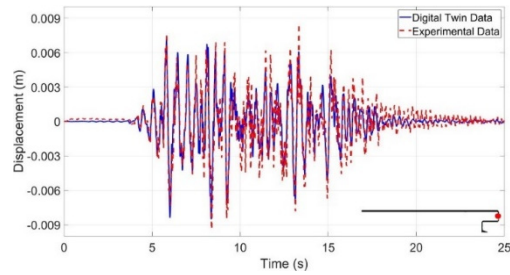
Fig. 15 Estimation of the external load using the digital twin system

### 3.3 Experimental results and discussion of the digital twin system

The digital twin system of the pipe was operated for 25 s using a damping ratio of 4%, as specified in Regulatory Guide 1.61 (Regulatory Guide 1.61 2007). The digital twin system estimated the external loads using the ground-acceleration response and acceleration response measured near the TMD. The estimated external loads are shown in Fig. 15. The estimated external loads and ground-acceleration response were applied to the digital twin system. The displacement estimated by the digital twin system and that measured on the pipe with the attached TMD are shown in Fig. 16. Table 4 lists the Root Mean Square Error (RMSE) values of the data shown in Fig. 16. Fig. 17 shows data comparing the estimated acceleration from the digital twin system with the accelerometer attached to the y-axis of the pipe. The data from the A8 sensor, utilized to estimate external loads, aligns well. Additionally, it can be seen that sensor positions A6, A9, and A10 follow the data trends well. However, a discrepancy exists between the accelerometer data at sensor locations A11 and A5. In the digital twin system, it was



(a) Y-axis response (D2 sensor)



(b) Y-axis response (D4 sensor)

Fig. 16 Comparison of the estimated displacement

Table 4 RMSE values of the digital twin data based on the experimental data

	RMSE value
Y-axis response (D2 sensor)	1.9636E-7
Y-axis response (D4 sensor)	1.4039E-7

assumed that the pipeline installed on the jig and hanger was fixed. However, in actual experiments, it is judged to be an error caused by the behavior of the pipeline connected to the jig and hanger. Consequently, the digital twin systems may have effectively predicted displacement data and showcased the utility of acceleration data.

The developed digital twin system could estimate the response at all points (Kim *et al.* 2023). To verify the response of the unmeasured points from the digital twin system, the estimated external load and measured ground-acceleration response were applied to the numerical model to compare the response of the unmeasured points. Fig. 18 shows a comparison graph of the unmeasured-point response of the pipe's numerical model and the digital twin, which represents the Y-axis displacement near the pipe boundary condition and Y-axis acceleration near the bending section of the pipe. The digital twin of the pipe predicted the stress at all points in real time using the estimated displacement. Fig. 19 shows the comparison of the stress estimated by the digital twin at the TMD installation and bending locations with the estimated stress. Table 5 lists the RMSE of the response and stress of the unmeasured points in the numerical model and digital twin.

The developed digital twin system can provide real-time information on the reliable responses of all points in a pipe system to the loads that act on it. Therefore, even in industrial pipes, a limited set of sensors can be used to estimate the responses of all points. Through such a response, monitoring a pipe that is subjected to multiple

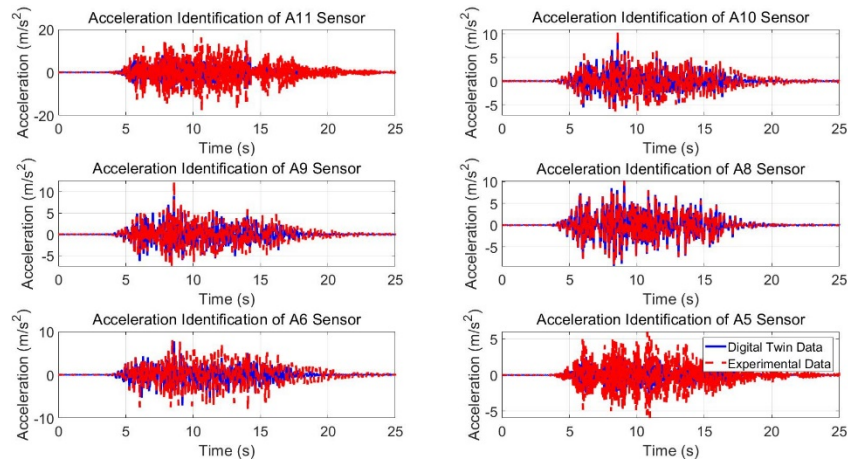
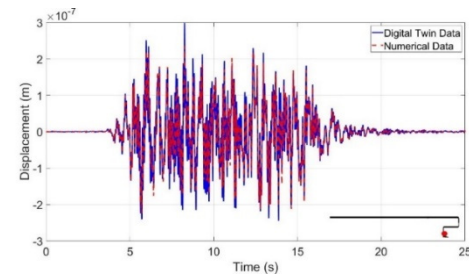
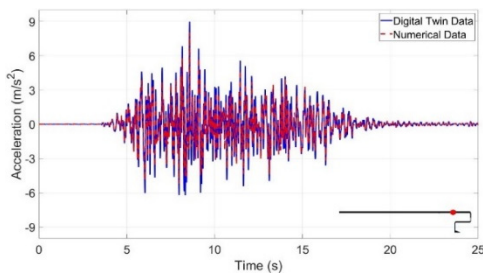


Fig. 17 Comparison of the estimated acceleration

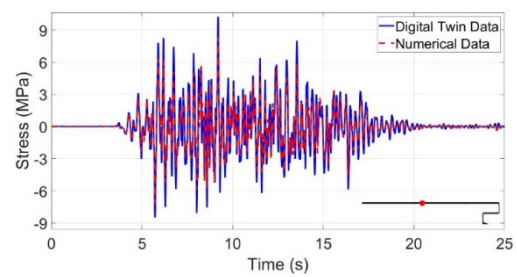


(a) Condition around the boundary

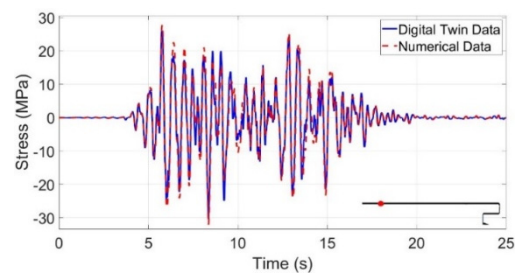


(b) Condition around the bending part in the pipe

Fig. 18 Comparison of the responses of the digital twin and numerical models



(a) Condition around the TMD in the pipe



(b) Location of the bend part in the pipe

Fig. 19 Comparison of the stress of the digital twin and numerical model data

loads in real time becomes possible, which enables the detection of potential failures and allows maintenance and repair work to be appropriately performed. Furthermore, this system would be highly advantageous in improving the safety and reliability of piping systems while also reducing operating costs.

The digital twin system can accurately predict seismic responses without detailed modeling that considers external loads such as TMDs, pumps, and motors. This system can benefit the SHM and safety assessment of pipes with attached rotating equipment. Therefore, proactive adoption and utilization of digital twin systems can enhance the competitiveness of the pipe industry and greatly assist in its safe operation and maintenance.

Table 5 RMSE values of the digital twin data based on the experimental data

	RMSE value
Around the boundary condition of the pipe (Fig. 17(a))	1.4474
Around the bend part in the pipe (Fig. 17(b))	1.5494
Around the TMD in the pipe (Fig. 18(a))	0.0075
Location of the bend part in the pipe (Fig. 18(b))	0.0015

#### 4. Conclusions

Pipes are crucial in social infrastructure facilities such as water supply, sewage, and gas heating. They are exposed to external loads such as earthquakes. Damage to pipes due to external loads can bring significant economic and social effects and can potentially cause accidents or disasters. Therefore, SHM technology for pipes is critical to prevent damage. The real-time response must be ensured to achieve automated SHM of pipes under external loads. However, the use of multiple sensors for health management poses economic challenges. Moreover, in some cases, directly measuring physical quantities is difficult because of spatial limitations. Therefore, techniques for estimating real-time responses are necessary to achieve the automated SHM and safety assessment of pipes subjected to external loads.

In this study, the proposed digital twin system could estimate real-time external load, responses, and stresses at all points in actual pipes subjected to earthquake and external loads using a minimum number of sensors. The developed digital twin system for installed pipes was validated by comparing the measured experimental and numerical-model data. The developed digital twin system could estimate the load, response, and stress in real time for pipes subjected to multiple loads, thereby saving time and cost. In addition, the digital twin system could construct a model that represents the behavior of a facility, allowing assessment of the facility status under various conditions without collecting actual data. Therefore, the developed digital twin system has demonstrated its potential as a technology that can contribute to facility maintenance and safety improvement.

By employing the constructed digital twin system, we anticipate that problems can be promptly detected by collecting and analyzing data in real time, in contrast to the traditional maintenance approach in existing infrastructure. Furthermore, the digital twin technology can be applied not only to pipes used in actual fields but also to various systems to estimate responses and stresses in real time. This ability can enhance the safety and reliability of the system by predicting the occurrence of damage and the useful life of the system. In addition, we expect the system to be used in various fields, such as harbors, shipbuilding, power generation, and manufacturing industries, by understanding the real-time status and safety of the system under various loads and environmental conditions.

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