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PIPING SYSTEMS OF INDUSTRIAL PLANTS SUBJECTED TO AXIAL AND SEISMIC INPUTS

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Abstract

Recent middle and intense seismic events worldwide have demonstrated that although current building regulations can significantly reduce human losses, earthquakes can still cause significant economic and functionality losses, affecting the resilience capacity of communities. A considerable portion of these direct and indirect economic losses are generated by affectation on business and industrial facilities. The latter are of special interest due to their high seismic vulnerability, leading to seismic-induced Na-Tech events (Natural Hazard Triggering Technological Disasters). Piping systems in industrial plants transport liquid and gases among different components. Any induced damage to these systems can lead to leakage of hazardous substances, which can cause fires, explosions, or starting a cascade effect along the industrial plant. Due to the complexity and vast possibilities of components and configurations of piping systems in industrial plants, there is a need for a better understanding of their seismic response; therefore, this study presents some of the results obtained from the experimental campaign conducted under the "MITPLANT- Seismic risk analysis and mitigation of industrial plants" project, in which several piping configurations were tested under axial and seismic inputs. These results are crucial for the development of calibrated numerical models and the seismic assessment and design of industrial plants.

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Keywords: steel pipes, *Na-Tech events*, industrial plants, nonstructural elements, experimental campaign.

1 INTRODUCTION

Recent moderate to strong seismic events worldwide have shown that, although current building regulations significantly reduce human casualties, earthquakes can still result in substantial economic losses, impacting the overall resilience of communities [1]. A considerable portion of these direct and indirect losses stems from damage to business and industrial facilities [2]. Industrial plants, in particular, are highly vulnerable to various natural hazards, such as earthquakes, floods, storms, and extreme temperatures, leading to so-called Na-Tech (Natural Hazard Triggering Technological) events [3]. Due to the complexity and diversity of components and configurations, industrial facilities exhibit high seismic vulnerability, which can result in structural collapses, explosions, fires, toxic releases, and more [4]. Among the various sources of vulnerability, the dynamic response of pipelines is especially critical during seismic events, as they are highly susceptible to damage [3]. Failures in pipes or their connections can cause loss of containment, leading to cascading effects and further damage to other components [5-7].

Despite the recognized importance of accurate seismic assessments of pipelines and their connections, the complexity of their components, joints, and geometries poses significant challenges for the development of reliable and manageable numerical models. Several authors have proposed calibrated and simplified models to simulate piping elements, especially considering geometrical variations and different joint typologies [8-10], nevertheless, more actual data is necessary for producing and improving modeling assumptions such as stiffness variations, inherent damping levels, hysteretic response, etc. This paper presents results from the experimental campaign conducted within the “MITPLANT - Seismic Risk Analysis and Mitigation of Industrial Plants” project, which involved testing several piping configurations under axial and seismic loads. These findings contribute to the development of calibrated numerical models and support the seismic assessment and design of industrial plants and piping systems.

2 EXPERIMENTAL CAMPAIGN

In order to obtain the seismic response of industrial pipelines, MITPLANT conducted two sets of experimental tests, cyclic axial tests and shake-table test. For both typologies of tests, several piping layouts (i.e., varying pipeline geometry) were constructed using welded and flanged joints. Pipes CHS-CF 114.3x3.6 made of S235 steel were used for both test typologies. Table 1 reports the main section’s properties of the used pipe and material. All pipeline configurations were welded in both ends to 22.0x22.0x2.0 cm steel plates that served as anchoring elements. The perpendicular length of all the specimens including the anchoring steel plates was equal to 410 cm. The welded connections were done using flux-cored arc welding, whereas the flanged connections were composed of PN16 steel flanges. Figure 1 shows an example of the tested specimens. In total six pipeline configurations were tested under cyclic axial conditions and six other pipeline configurations were subjected to actual seismic inputs. All the tests were conducted at the Eucentre Foundation in Pavia, Italy.

Table 1 Pipe section properties

Pipe	Outer diameter	Thickness	Area	Moment of inertia	Radius of gyration	Yield strength
	mm	mm	cm^2	cm^4	mm	MPa
CHS 114.3x3.6	114.3	3.6	15.52	191.98	39.2	235

Figure 1 Example of the pipeline configuration specimens.

2.1 Cyclic axial setup

Three pipeline layouts using welded and flanged connections (i.e., six specimens in total) were tested following a cyclic axial protocol. The loading protocol was taken from the FEMA 461 document [11] as recommended by [12] following a displacement control procedure. Furthermore, it was modified to consider only tension displacements to avoid premature failure due to critical loads. Figure 2 shows the used loading protocol. The three pipeline layouts simulated a straight pipe (Figure 3), an Omega joint (Figure 4), and a V joint (Figure 5). Finally, an example of the final test setup is shown in Figure 6.

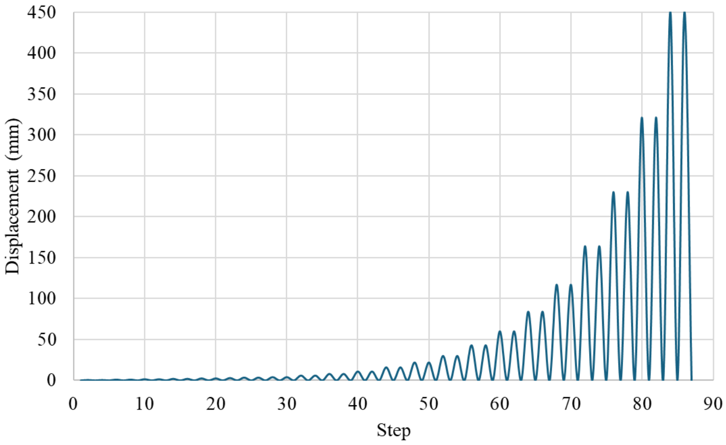

Figure 2 Loading protocol for the axial test.

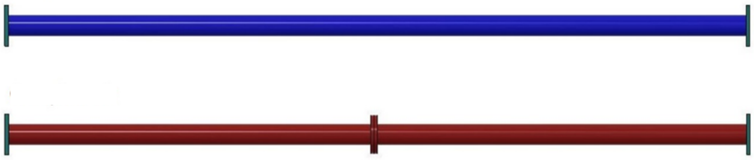

Figure 3 Straight pipe configuration.

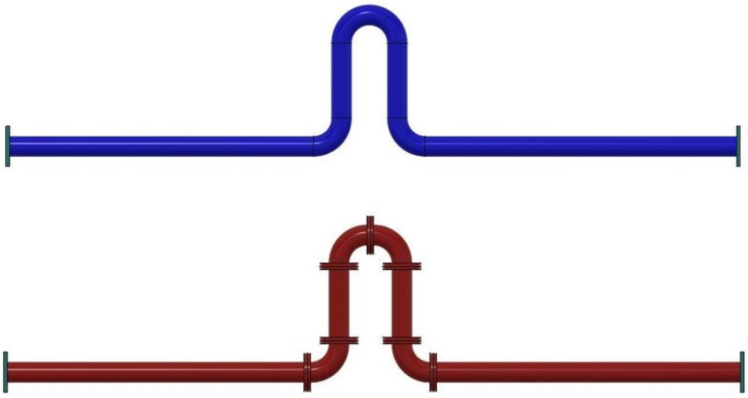

Figure 4 Omega joint configuration.

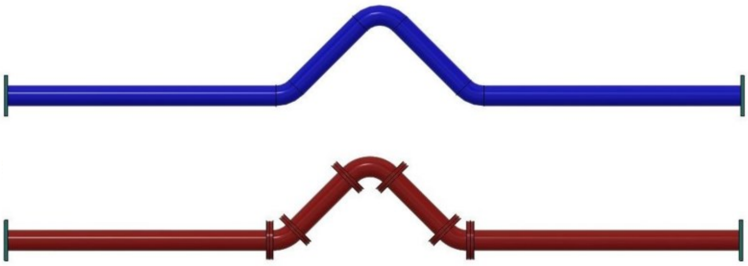

Figure 5 V joint configuration.

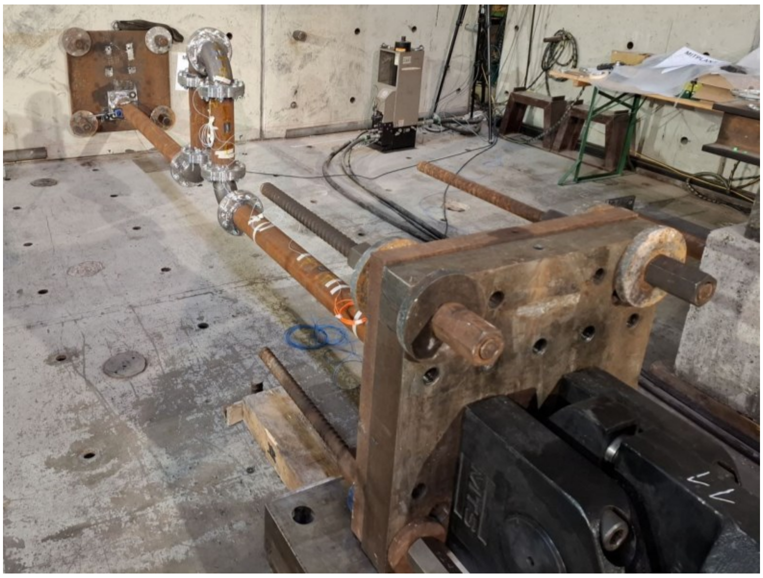

Figure 6 Example of the cyclic axial test setup.

2.2 Shake-table test

Three pipeline layouts were subjected to horizontal seismic inputs using the 9D shake-table available at the Eucentre Foundation. This shake-table is able to simulate different seismic inputs in two independent parallel shake tables one 4060 mm above the other one. Figure 7 shows an example of the shake-table setup. In order to better represent the actual seismic demand of industrial pipelines, a 3D two-story steel frame was designed and subjected to nonlinear time-history analysis using horizontal ground motions. Figures 8 and 9 show the steel frame and the input and floor response spectra of the selected ground motion. The steel frame was composed of IPE 330 and HEB 360 profiles for the beams and columns, respectively, and was characterized by fundamental periods in both translational directions equal to 0.41 s and 0.31 s. The structural elements were characterized by a steel S235 and the nonlinear behavior was modeled using fiber sections.

Figure 7 Shake-table test setup.

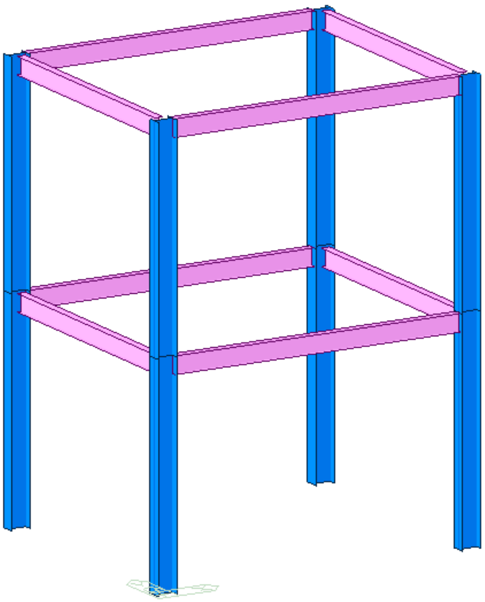

Figure 8 Steel frame modeled to obtain floor motions.

The pipelines specimens were assumed to be attached to the first and second floor, therefore, the respective floor motions were used as seismic input for the shake-table. The pipeline specimens were subjected to scaled floor motions from 10% to 140% of the selected record. The three pipeline layouts simulated an Omega joint (Figure 10), a V joint (Figure 11), and a 3D piping layout composed of straight pipes and 90 degrees elbow connections (Figure 12).

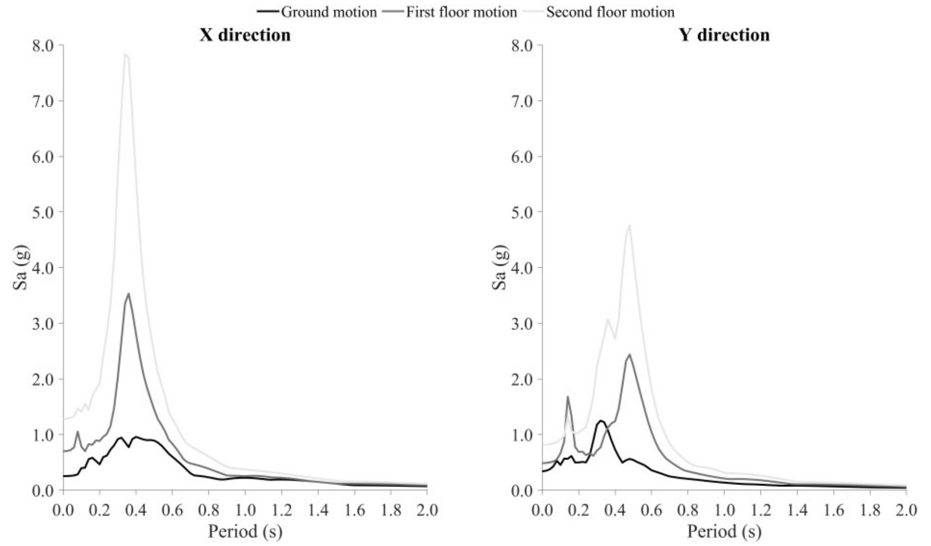

Figure 9 Seismic input and floor motions.

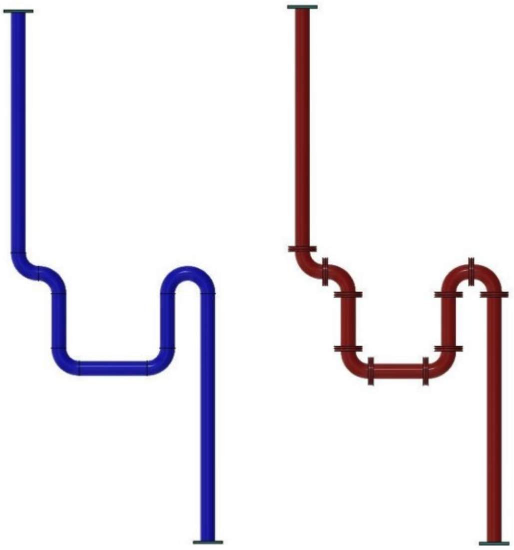

Figure 10 Omega joint configuration.

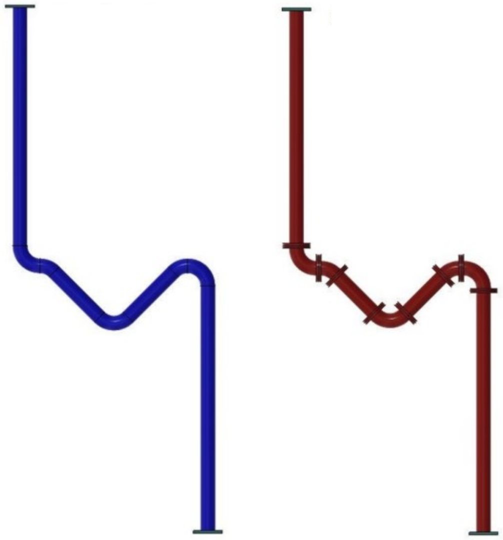

Figure 11 V joint configuration.

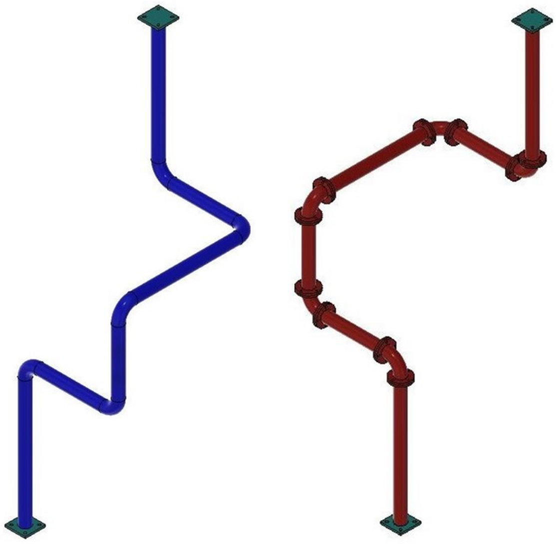

Figure 12 3D specimens.

3 RESULTS

The results obtained from the experimental campaign depend on the test category, for instance, for the cyclic axial test, displacement, force, and strain in critical points were saved, while for the shake-table test, the pipeline specimens were equipped with three-axial accelerometers, and displacements and strains were measured in critical points.

3.1 Cyclic axial test

Figures 13 to 15 show some examples of the results obtained. As expected, the straight specimens exhibited larger axial stiffness and peak forces than those of the pipelines with Omega and V joints. In addition, no failure was observed on the straight specimens as the test was interrupted due to instability of the specimen generated by compression forces. It is important to notice that although the cyclic test protocol did not include compression displacement, the elongation in the pipe elements once the yield strength was reached caused a compression force as the actuator returned to the zero displacement. This compression force was large enough to reach the critical load of the specimen. Moreover, in the case of the pipelines with Omega and V joints with welded connections, a large axial deformation of the curved elements was observed. The pipe with the welded Omega joint did not exhibit a rupture before reaching compression critical load. Conversely, the pipe with the welded V joint exhibited a rupture of one of the welded connections. Figures 16 and 17 illustrate the final state of the welded specimens. On the other hand, the pipelines with flanged joints exhibited local buckling of the curved elements generated by the abrupt change of stiffness between the pipe and the flanges. Failure of the pipe was observed in the transition area as shown in Figures 18 and 19.

3.2 Shake-table test

In general, no apparent damage was observed on the different specimens tested on the shake-table. The specimens with flanged connections exhibited larger induced acceleration compared to those with welded connections, nevertheless, both results had the same order of magnitude. Figures 20 and 21 show examples of the induced acceleration results. A similar trend was exhibited by the displacement response in the in-plane direction, in which the welded specimens had smaller displacements compared to those of the flanged specimens. Figure 22 shows an example of the in-plane response of the piping elements.

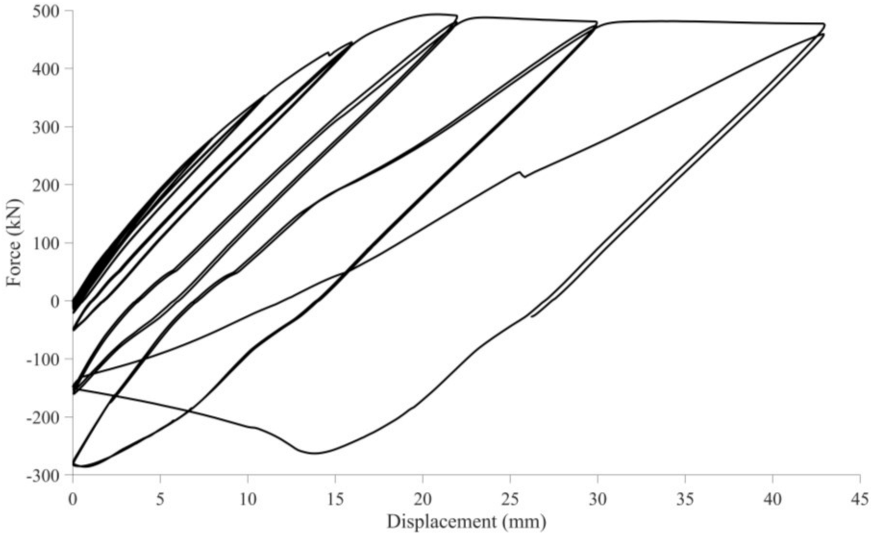

Figure 13 Force - displacement curve of the straight pipe with a flange in the middle.

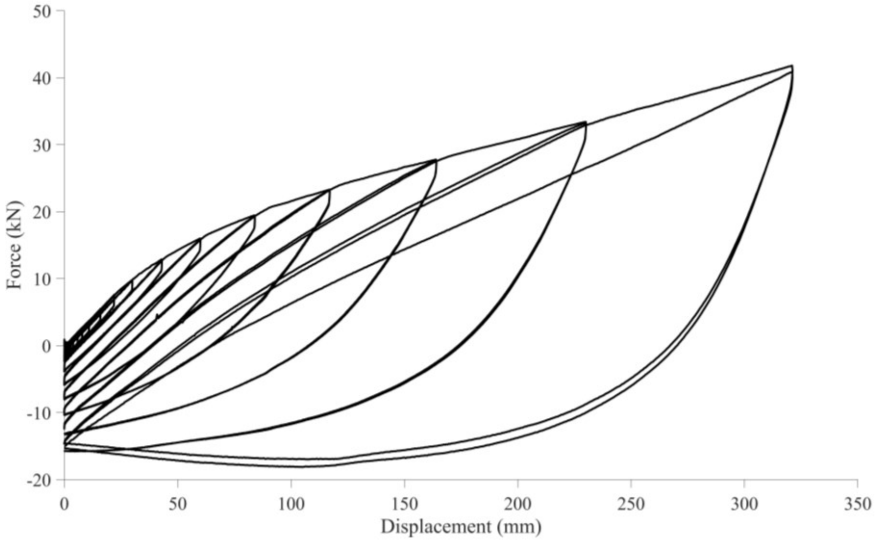

Figure 14 Force - displacement curve of the pipe with a welded Omega joint.

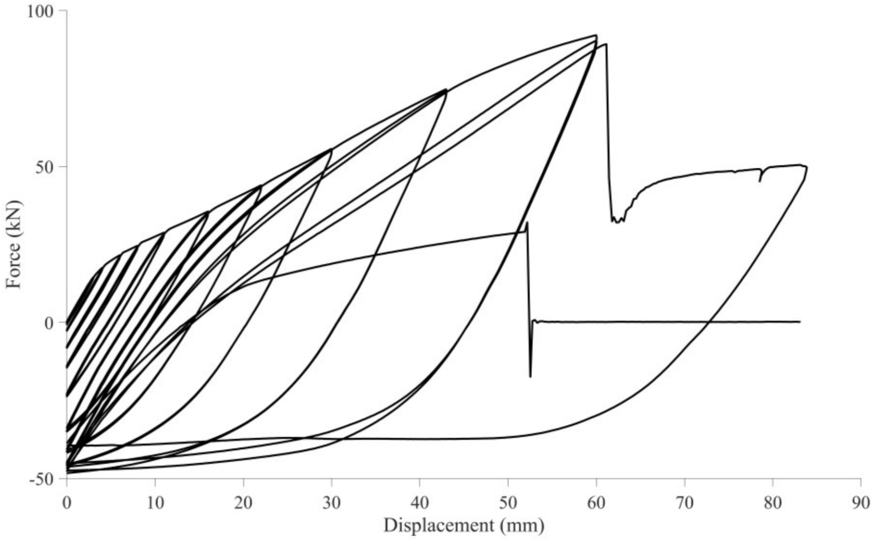

Figure 15 Force - displacement curve of the pipe with a flanged V joint.

Figure 16 Final state of the pipe with the welded Omega joint.

Figure 17 Final state of the pipe with the welded V joint.

Figure 18 Final state of the pipe with the flanged Omega joint.

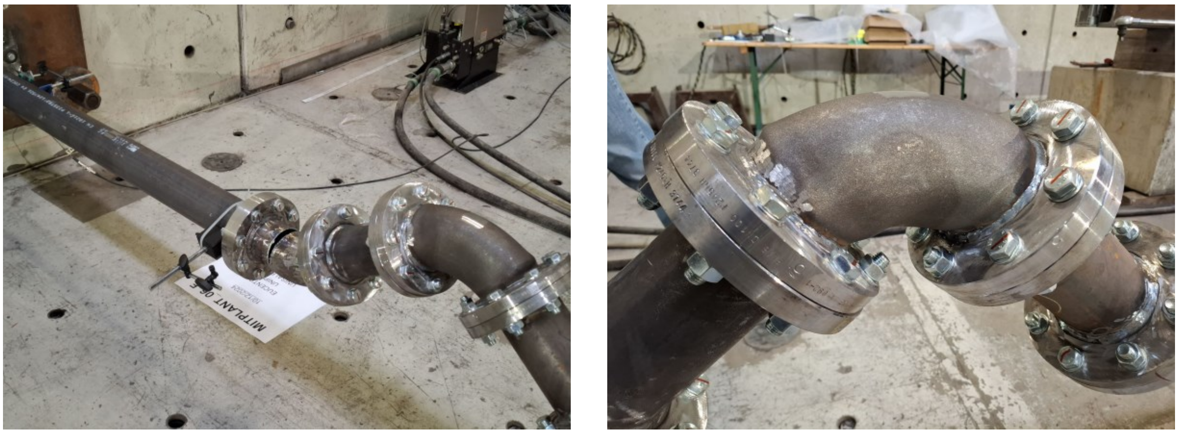

Figure 19 Final state of the pipe with the flanged V joint.

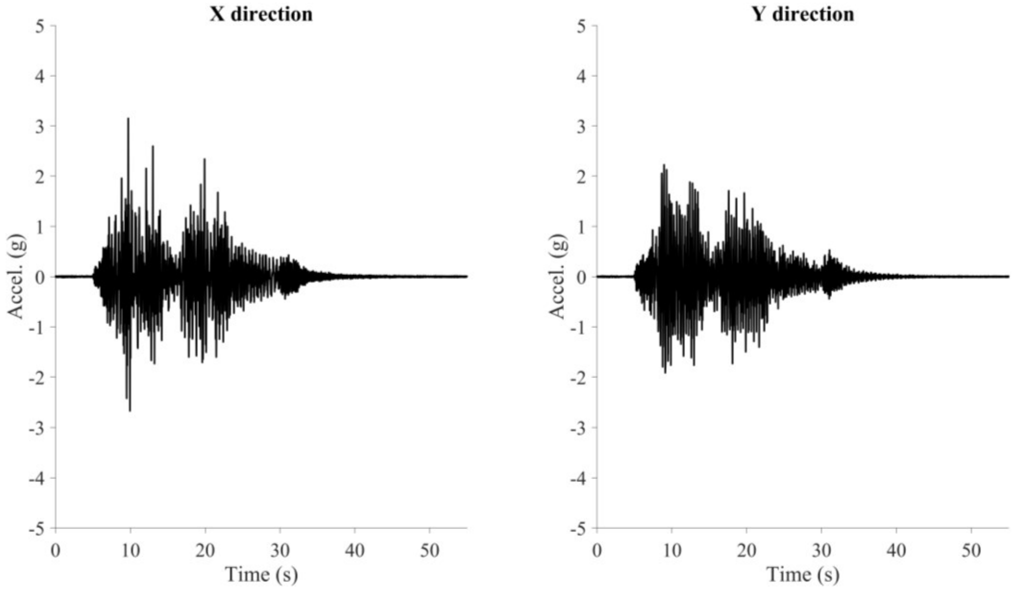

Figure 20 Acceleration response of the 3D specimen with welded connections.

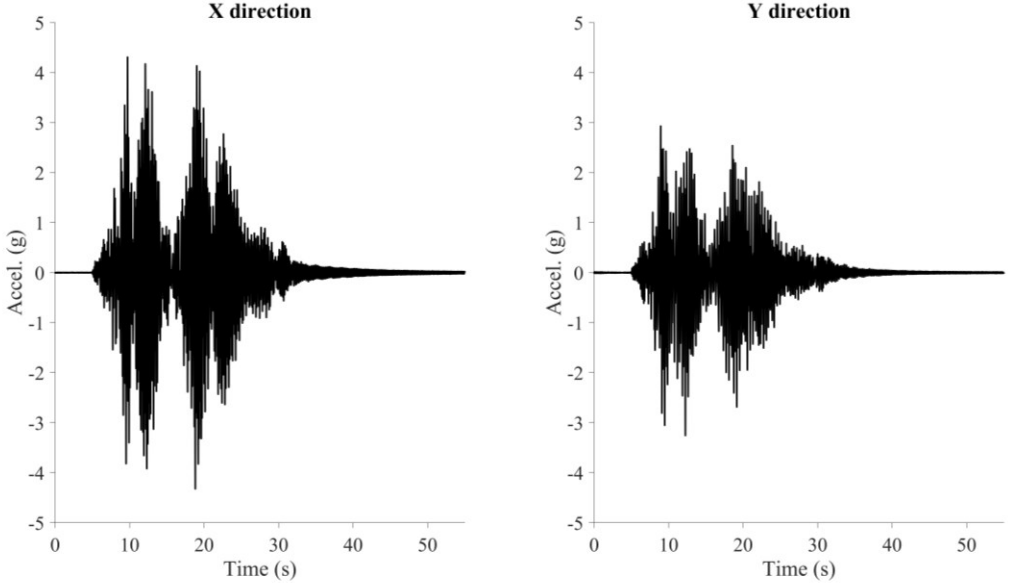

Figure 21 Acceleration response of the 3D specimen with flanged connections.

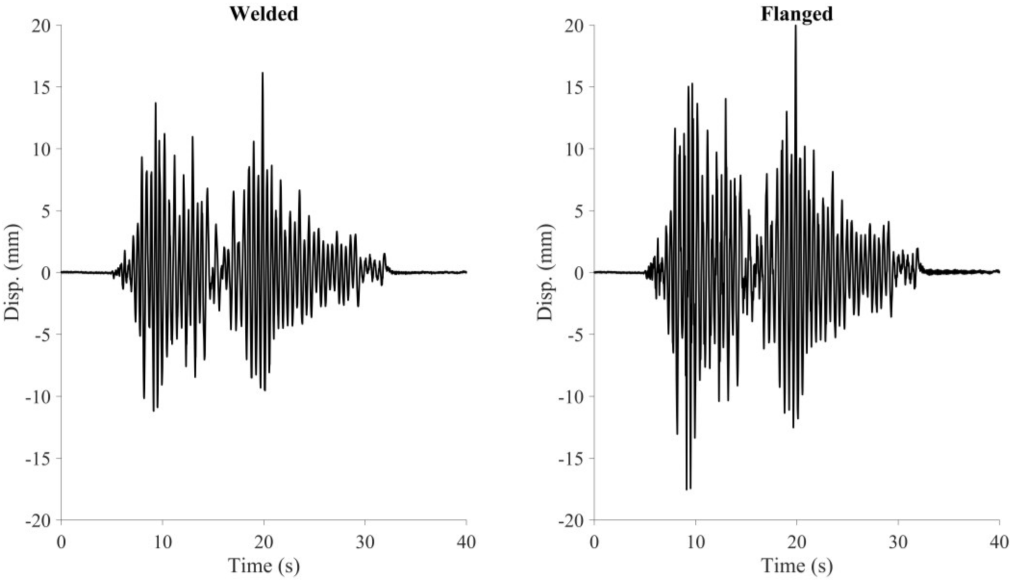

Figure 22 In-plane displacement of the specimens with V joints.

4 CONCLUSIONS

Na-Tech disasters triggered by seismic events can significantly impact the resilience of societies and communities. In this context, industrial plants, and particularly their pipeline systems, represent critical components in seismic risk modeling due to their high vulnerability and structural complexity. Therefore, it is important to have accurate and calibrated models able to capture their seismic response and failure mechanisms. Such models require input data for their development and calibration, making it important to conduct experimental campaigns on diverse pipe configurations and layouts. This article introduces the experimental results carried out under the framework of the project: MITPLANT- Seismic risk analysis and mitigation of industrial plants, in which several piping layout and typologies of connections were subjected to axial and seismic inputs. In general, the results show that flanged connections tended to exhibit larger seismic responses and failed sooner than the equivalent specimens equipped with welded joints. In specific, under axial-tension loads the welded joints exhibited longer maximum displacements before failure compared to those exhibited by the specimens with flanged joints. In addition, the Omega joint exhibited a larger flexibility compared to the V joint. Regarding the shake table test, the specimens with flanged connections exhibited larger induced displacements and accelerations than those exhibited by the specimens with welded connections. The authors state that the results of the different tests can be shared under reasonable requests to the corresponding author.

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