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Hybrid simulation of a pipeline linking two structures within a natural gas processing plant

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Abstract

Though often overlooked, the impact of transient ground deformation on natural gas (NG) pipelines, especially elbows, can be highly adverse. During a moderate intensity earthquake event, elbows may be damaged by the forced out-of-phase movement between their two ends. This paper investigates in a hybrid computational-experimental manner the scenario wherein an NG pipeline segment connects two major structures in a plant: a steel-structure compressor house and a steel platform topped with large reliquefaction condensers. Two 90-degree elbows are included in the pipe segment of interest, accommodating the staggered relative position between the pipe rack on the compressor house and the pipe nozzle on the exposed large equipment. Given that the connecting pipe extends across both structures, the latter is expected to interact against each other during an earthquake, thus producing non-negligible strain to the elbows that need to be quantified. Due to the complex pipe elbow behaviour, its nonlinear response may also affect the response of the pipe itself, as well as that of the structures that the pipe is connected to. As a result, it is a potentially vulnerable structural component within an NG compressor station, which can lead to long-lasting service downtime or possible secondary hazards. The degree of damage potential on elbows, induced by ground motion, may depend on many factors. Assuming the structures behave elastically, preliminary numerical simulations revealed two most significant elements affecting the development of strain at elbow flanks: namely the simultaneous mobilization of divergent structural oscillation between the two supports and the relative stiffnesses of the pipe and of the structures. Numerical analyses found that the unfavourable pipe-structure interaction can lead to substantial differential motion at two pipe-ends due to the out-of-phase structural vibration, and hence a higher elbow seismic demand. To examine the above issue, hybrid simulation is employed, substructuring the problem between a physical specimen of the coupling pipe including two elbows that are tested at the University of Patras and the two structures, their foundation and the supporting subsoil that are analysed numerically. More precisely, a pipeline of 21.96 mm in diameter and 6.3 mm in wall-thickness links two structures located at a distance of 7.56 m with respective frequency ratio equals to 0.7. The results of the hybrid simulation confirmed the accuracy of numerical prediction and verified the importance of pipeline-structure coupling effects.

Keywords: Hybrid simulation; natural gas pipeline; elbows; UT-SIM; seismic assessment

1. Introduction

Coupled behaviour of a complex piping system has been studied in the past, where the pipeline is treated as a secondary system or internal equipment that is mounted onto the primary structure [1][2]. It is often the case that the attachment points of the pipeline are displaced synchronously during an earthquake, such that the two ends of the pipe have no substantial relative deformation. In such cases, a realistic earthquake will not trigger the same amount of high axial compression or bending moment that are commonly employed in a monotonic or cyclic elbow specimen test [3]. Concerning this matter, the seismic behaviour of pipelines affected by external geometrical nonlinearity has been placed under scrutiny, where an elevated seismic demand for above-ground piping systems [4][5] and buried pipelines [6][7] subjected to differential end movements have been observed both numerically and experimentally. In the present work, a critical scenario of a natural gas (NG) pipeline coupling two industrial structures that are typically found in an NG processing plant is studied. High strain and cross-sectional ovalization on the elbows are anticipated during an earthquake due to the different dynamic characteristics of the two supporting structures and their subsequent out-of-phase oscillation. The presence of pipe stiffness is found pronounced such that the interaction effect between the linking pipeline and the two supporting structures are considered non-negligible. An experimental study is presented in this paper which examines the response of the pressurised pipeline segment including two 90-degree elbows that bridge two major structures within an NG plant. The simulation is conducted as an experimental-numerical hybrid simulation, where the coupling effect of the pipe (tested physically in the University of Patras) and its supporting structures (numerically modelled by the University of Toronto and the University of Bristol) are considered. The experimental configuration, the computational framework and the main observations made are outlined below.

2. Experimental Setup

2.1 System substructuring

Two substructure modules, which correspond to the pipeline itself and the remainder of the system (i.e., the two interacting structures), were configured for the pseudo-dynamic hybrid simulation in order to investigate the coupled response of two structures linked by the pipeline segment. In the hybrid simulation, the pipe component was experimentally tested, while the rest of the system was numerically analysed as will be described in the following sections. Fig. 1 illustrates the coupled system's substructuring scheme used for hybrid simulation.

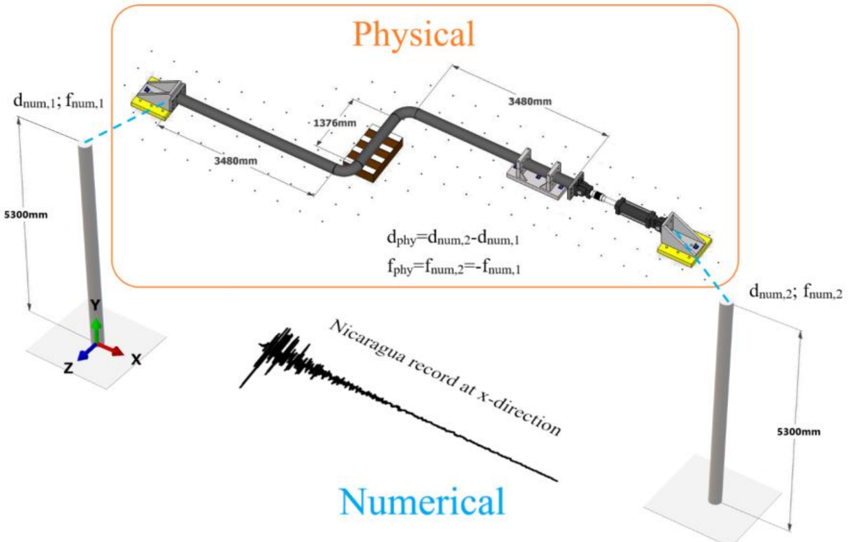

Fig. 1 – Layout of the pipe-structure substructuring for the hybrid simulation.

The generalised hybrid simulation framework UT-SIM (www.ut-sim.ca) developed by the University of Toronto research group [8][9] was used for integrating the numerical and experimental substructures for the hybrid simulation. The UT-SIM framework employs the University of Toronto Networking Protocol (UTNP), while the software library provides useful functions in exchanging data between diverse numerical and experimental models. The implementation of the presented hybrid simulation is illustrated in Fig. 2. OpenSees [10] computational platform is selected to perform the analysis task of both the main integration module and the numerical substructure modules. In this scheme, the generalised nature of UT-SIM framework assigns each module with an interface of communication. An interface element termed as *SubStructure* element is featured to the OpenSees main integration module to collect the restoring force and stiffness matrix of the physical substructure module through the UTNP, whilst a network interface for the controller (NICON)[11], that is based on *LabView* programming environment and *National Instrument* hardware, allows the communication, coordinate conversion, analogue voltage generation, data acquisition and feedback of measured data from the physical substructure module. Prior to the experimental-numerical hybrid simulation, ABAQUS-OpenSees multi-platform simulations where the test specimen is also analytically modelled in ABAQUS were conducted to make sure the smooth operation of the substructuring scheme.

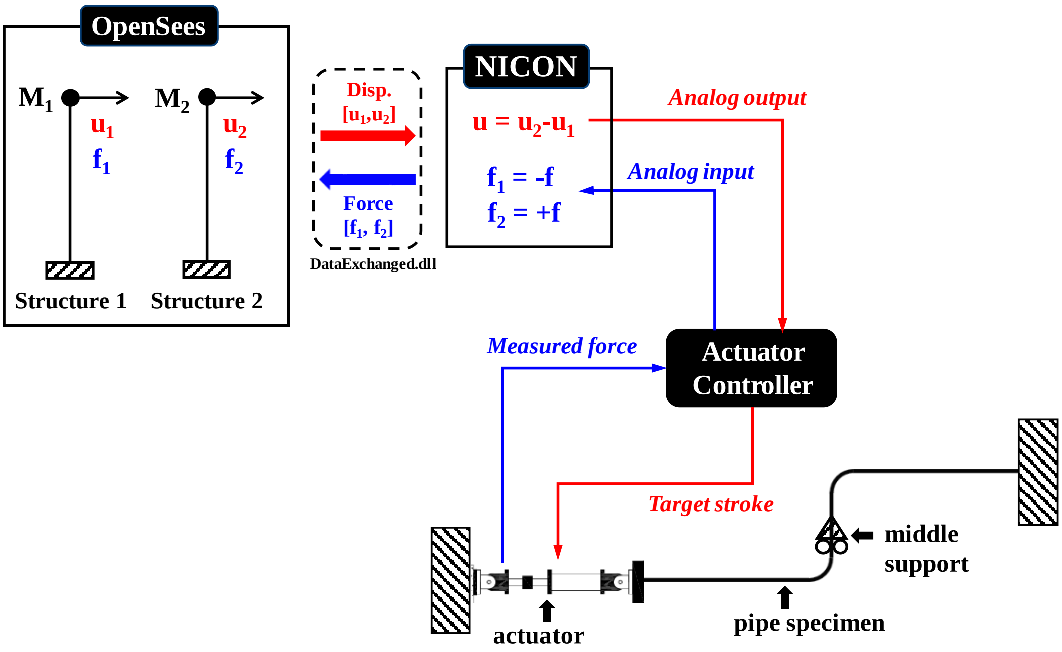

Fig. 2 – Hybrid simulation setup.

2.2 Integration module/Numerical substructure module

Due to the fact that the investigated critical scenario presented herein emphasises an unexpected damage potential of industrial pipe within NG plants, which is a problem only meaningful given the structures are not posting a threat to the security of the NG plant in the first place, the supporting structures are assumed to behave as elastic systems. As such, they can be modelled with Elastic Timoshenko Beam-Column Elements and lumped mass, whose bases are considered fully fixed. At the top of the numerically modelled structures in OpenSees, a dedicated *SubStructure* element is defined, acting as the interface of communication at the integration module. Structure 1 has a natural frequency of f_1=3.3 Hz and mass of M_1=122.5 tonnes; structure 2 has a natural frequency of f_2=2.3Hz and mass of M_2=79.8 tonnes. The numerical model is assigned with 2% Rayleigh damping. Alpha - Operator Splitting method [12] is used as the numerical integration algorithm (see Fig. 2).

In the absence of known fixity conditions, the two pipe ends are assumed to be fixed at all DOFs except for the rotational DOF along Z-axis. This fixity condition is adopted because the two supporting structures are expected to deform in shear. Under such an assumption, the structures' floors, on which the extended pipeline are attached to, are parallel to the flat ground surface throughout the time history. It is assumed that the ground excitation is in the *x*-direction as shown in Figure 1, along which the buildings can only deform. This simplification ensures the compatibility and equilibrium conditions at the coupling nodes for using a single unidirectional actuator in the physical substructure of hybrid simulation. The first 7 sec of the ground motion from the 1972 Nicaragua Earthquake recorded at Managua ESSO station is used as the input motion. The predominant frequency of this ground motion is approximately 2.25 Hz. The PGA of the motion is scaled to 1.0 g (Fig. 3). A total number of 1,000 steps makes up the complete 10-sec analysis. The numerical integration time step is selected to be 0.01s. Preliminary analyses have verified the accuracy of using the time step.

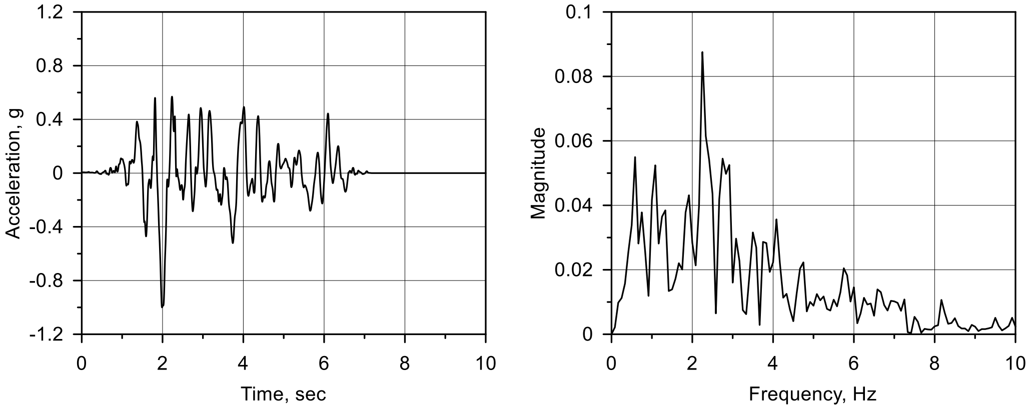

Fig. 3 – Input ground motion for the hybrid simulation and its Fast Fourier Transform amplitude diagram.

2.3 Physical substructure module

The physical substructure module comprised the bridging NG pipeline segment between the two supporting structures. The pipe (See Fig. 1), welded in-situ at the Structures Laboratory of the University of Patras, includes three straight pipe segments and two 90-degree elbows with a cross-section of 219.6 mm external diameter (D) and 6.3 mm wall-thickness (t). The length of the shorter straight pipe near the centre is 1.38 m, whereas the length of the two long straight pipe segments is 3.48 m. The bending curvature of the 90-degree elbows (R) equals to 302 mm. Therefore, the perpendicular distance between the two structures is 7.56 m, the value of pipe nondimensional geometry parameters are R/D = 1.38, D/t = 34.86 and the elbow bend factor $h = Rt/(D/2)^2 = 0.158$. The pipe specimen is rigidly clamped onto the strong floor through a triangular connector component at one end. The other end is attached to a unidirectional hydraulic actuator for applying end-displacements (Fig. 4, left). An in-house pressurising system applied internal water pressure of 3.0 MPa, simulating the pressurised NG inside the pipe, whose magnitude was monitored throughout the experiment. Two supports with lubricated flat surfaces, simulating a pipe supporting rack, are placed under the middle part of the pipe specimen. The supports provide constraint in the vertically downward direction, so that initial pipe flexure due to self-weight and water is prevented before the hybrid simulation. A restraint device guides the movement of the straight pipe segment linking the actuator to an axial-direction-only mode to accurately control the boundary condition between the physical and numerical substructures (Fig. 4, right). As the restraint device is in contact with the pipe specimen, a contact force with unknown magnitude will also be included in the restoring force sent back to the integration module at every time step due to the potential uplifted or horizontally inclined positions of the pipe specimen during the test, which could impact the numerical time integration. While all contact surfaces are highly lubricated to reduce friction, restraint on the pipe are also left untightened to reduce the effect further. As it is shown, the top half of the two restraint hoops rest in place only due to self-weight. Preliminary non-damaging, small-amplitude hybrid simulations were conducted to investigate the impact of the friction which will be presented later. It is concluded that the effect of the additional contacting force is insignificant with the semi-restrained condition described above. In the actual hybrid simulation, the uplift of the upper-half of restraint device was not observed.

Fig. 4 – Physical substructure module (left) and the auxiliary restraint device (right).

The small-amplitude hybrid simulation also confirms the stability of the numerical integration scheme which ensures smooth operation of all components, as well as exempting the hybrid simulation from potential control errors, which may depend on working frequencies and amplitudes, the specimen, the actuator, the control device, the control algorithm, its parameter setting, as well as the selected size of the rising and holding periods [13]. Through calibration, appropriate parameters of the PID controller, velocity of the actuator and maximum allowable amplitude of the input motion were determined before the actual hybrid simulation. While the capacity of the actuator itself supports high velocity, excessive actuator speed may bring significant fluctuation to the force and displacement readings upon completion of the current time step's prescribed displacement instructed by the integration module. An erroneous measurement of restoring force feedback entering the equation of motion can then impact the accuracy of the simulation. On the contrary, slower actuator speed generally enhances the quality of feedback measurements but elongates the testing time too. In the trade-off between accuracy and efficiency, an appropriate maximum actuator speed was selected equal to 1 mm/s, and a waiting time of 5 s is used after each execution of prescribed displacement to reduce the undesirable fluctuation of forces. The average force measured for 2 sec period after imposing the command deformation is fed back to the numerical integration scheme. Such configuration ensures accurate feedback information from the physical substructure module to the integration module, while compressing the execution time of the full simulation within about 7 hours of wall-clock time. Moreover, the initial stiffness of the physical substructure module, required as an input by the numerical integration module for using the Alpha - Operator Splitting method, is experimentally measured in the preliminary small-amplitude test.

During the hybrid simulation, the measured reaction force and the displacement of the specimen are fed back to the numerical integration scheme for advancing the solution to the next time step. Since a single actuator is applying prescribed displacement to the physical specimen and the other end of the pipe is fixed to the laboratory floor, the relative displacement between the two supporting structures is imposed to the specimen (see Fig. 2).

2.4 Numerical verification of the hybrid simulation

Numerical verification of the hybrid simulation is done using the general-purpose finite element analysis package ABAQUS [14]. Comparison of relative displacement time history between the holistic pipe-structure model and the stand-alone structures with no pipe (Fig. 5, left) showed a clear sign of the coupling effect between the two supporting structures. The coupling effect is introduced by the linking pipe. Existing design criteria require that for the case of a secondary system attached to a primary system, the evaluation of coupling effect can only be neglected if the total mass of the interacting secondary system is less than 1% of the primary supporting structure [15][16]. Nonetheless, it has also been pointed out that if the secondary system is supported at two or more locations, the coupling effect shall be investigated regardless of any mass percentage value [1]. Fundamentally the behind-the-scenes indication is that, if a decoupled analysis is carried out, it is vital to ensure the decoupling does not significantly affect the frequencies and the response of the primary systems [17]. Cautiousness is indispensable when evaluating the selected critical scenario herein, where the secondary system is attached to two distinctive structures and is excited at two ends by the out-of-phase oscillations of the latter. Preliminary analyses show that while the natural frequencies of the two structures are not altered dramatically, the deviated response means that a coupled analysis, using hybrid simulation technique, is appropriate and necessary for the tested scenario.

Numerical analysis imitating the experimental conditions with explicit modelling of the actual physical supports and restraint devices used in the hybrid simulation was conducted (Fig. 6, left), along with another branch of numerical simulation in which the model is built as close as possible to the original problem itself (Fig. 6, right). Comparison of these two types of numerical analyses helps to quantify explicitly the effect of contacting force raised by the physical supports and auxiliary restraints used during the experiment, which may deviate the result of the test-condition case from the original physical problem case. In the course of numerical validation, the pipe is modelled with four-node reduced-integration shell element, S4R, assigning plastic material properties with linear kinematic hardening rule, whilst the structures are modelled with elastic beam element and lumped mass. Rayleigh damping of 2% is applied for both models. Linear brick element with 8-node, reduced integration and hourglass control, C3D8R, was used to model the auxiliary supports and restraints in the test-condition model. Basic Coulomb friction definition is employed with a friction coefficient (FC) of 0.6 between the contacting surfaces, which is a typical value for steel-to-steel static friction that is compatible with the pseudo-dynamic nature of the experiment. As in the actual experiment, all contacting surfaces are lubricated, the contact effect considered in the numerical analysis is much biased toward the conservative side (Fig. 5). It is confirmed that the deviation brought by auxiliary boundary conditions necessary for the experiment is relatively small from the original physical problem, with up to 4% of maximum relative displacement and 7% of maximum reaction force differences. Observations during the preliminary non-damaging small-amplitude hybrid simulation as well as the full-amplitude one, confirmed a 2% deviation of measured maximum reaction force introduced by the friction at the supports. Given the above discussion, it was concluded that test results obtained from the hybrid simulation are valid.

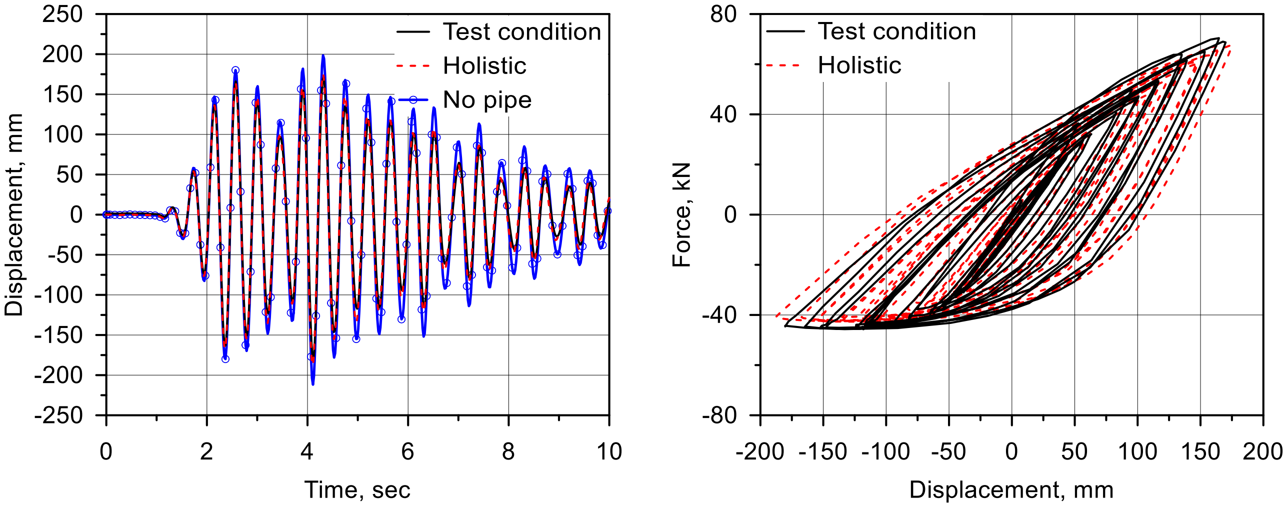

Fig. 5 – Effect of boundary conditions brought by auxiliary experimental gears: Time histories of relative displacement between two supporting structures (left) and force-displacement curves (right) from the FE model built to test-conditions and the FE model built to the physical problem.

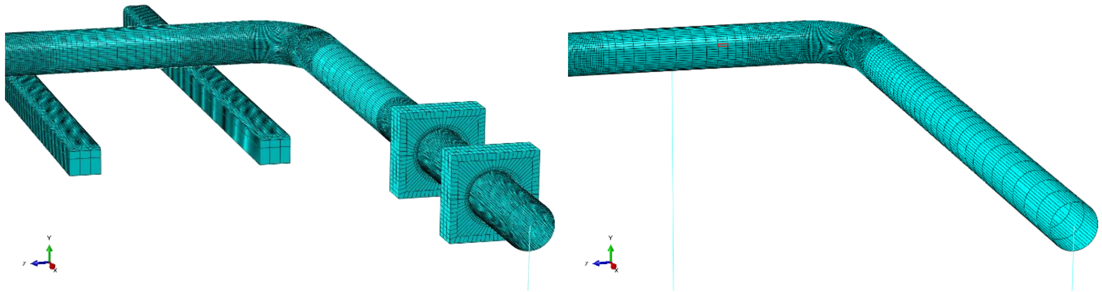

Fig. 6 – A pair of typical numerical models built to the experimental condition (left) and built to the physical problem (right).

2.5 Instrumentation

2.5.1 Strain gauges

A 16-channel data acquisition system for strain measurement is used for the test. The strain gauges are installed as shown in Fig. 7. The four locations with significant strains on a half-elbow are identified based on the numerical analyses. Because of the possible out-of-plane deformation of the pipe and the existence of the restraint device, the pipe specimen may behave unsymmetrically despite its symmetric geometry. Thus all four geometrically symmetrical half-elbows are instrumented with strain gauges at the same locations to ensure the measurement of maximum strains on the elbows.

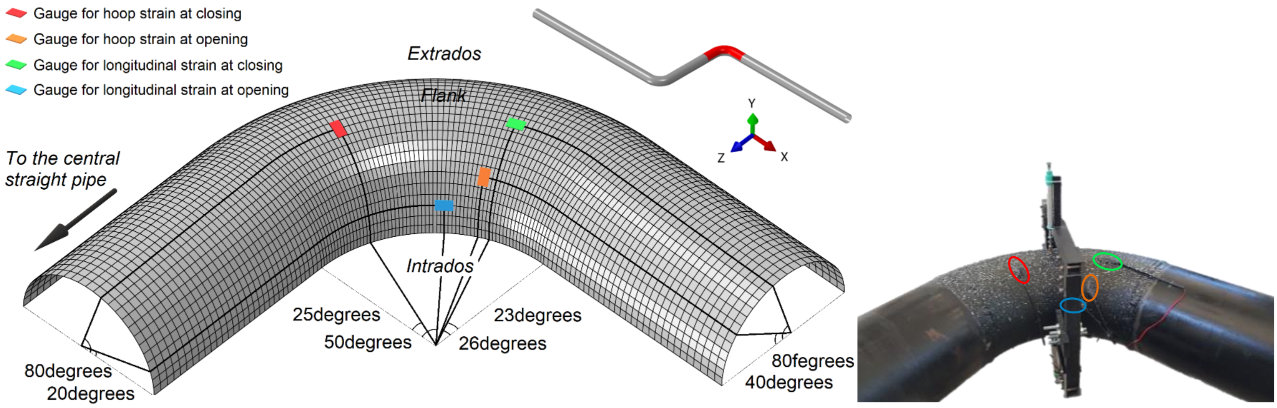

Fig. 7 – Outline of strain gauge placement on one of the half-elbows (left) and strain gauge implementation on the actual specimen (right).

2.5.2 Ovalization measuring device

Two special-purpose ovalization measuring devices (one per elbow) with linear voltage differential transformers (LVDTs) are used in order to measure the development of cross-sectional ovalization on the elbows (Fig. 8). The main body of the ovalization measurement device is a light steel frame which is in contact with the elbow at four points along the perimeter of a single cross-section: the frame is welded to the elbow at its intrados, whilst displacement measurements are taken at the elbow's extrados and two flanks. The steel frame itself is considered rigid, allowing the LVDTs to be pressed against the elbow wall, thus obtaining the correct measurement of elbow cross-sectional diameter change, or "flattening" [3], at two perpendicular diameters. Because the welded auxiliary frame could potentially influence the response of the pipeline, numerical analyses were performed to investigate the location where the welded frame does not significantly influence the measured strains. It was found that while a somewhat most favourable location is possible to be determined for the measurement quality of a single strain gauge, a best ovalization device location for overall measurement quality is blurred. And it is believed that the alteration of pipe response due to different locations of the measurement gears is minor. In pursuit of the overall benefit of both ovalization and strain measurements, the two ovalization devices are installed in the middle section of the elbows, where maximum elbow flattening occurs according to numerical predictions.

Fig. 8 – Ovalization measuring devices.

3. Test Results

3.1 Relative displacement time histories and force-displacement curves

Relative displacement (Fig. 10, left) and force-displacement responses (Fig. 10, right) obtained from the hybrid simulation (HS) are presented to gain insight into the hysteretic response of the linking pipeline. The former indicates system response on a global level and shows a clear sign of pipe-structure interaction when compared against a no-pipe simulation case, whereas the latter reveals evident hysteresis behaviour of the nonlinear pipe itself. It is also noted that while the ABAQUS model of the holistic pipe-structure system predicted well the amplitude of relative displacement time history, the experimental result showed a slightly higher vibration frequency.

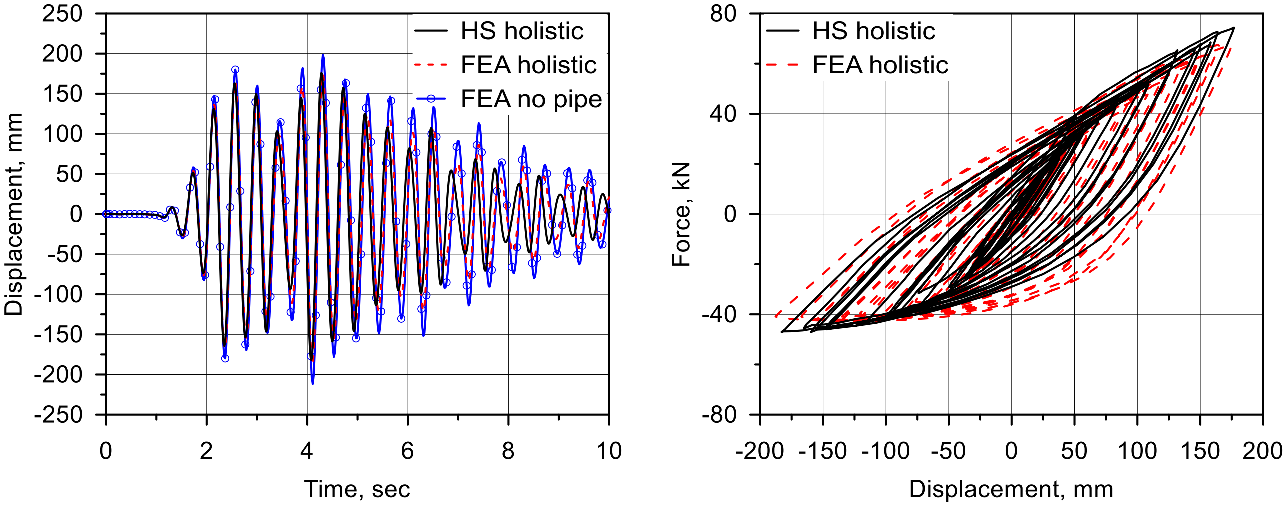

Fig. 10 – Time history of relative displacement between two supporting structures (left) and Force-displacement curve (right) from the hybrid simulation.

3.2 Strains on elbows

Four groups of strains were monitored at the top and bottom surfaces of the two elbows, in case the physical specimen behaves unsymmetrically in the hybrid simulation due to the constraint device. Despite this concern, the slightly biased boundary condition of the physical specimen is proven to have little effect on the response. From the measurements, the strains were found symmetric with respect to the axis of the symmetry of the specimen. Critical hoop strain measurement from the hybrid simulation, sampled at the location corresponding to where the maximum hoop strain is observed in numerical predictions when the elbows were subjected to closing bending moment, is plotted in Fig. 11.

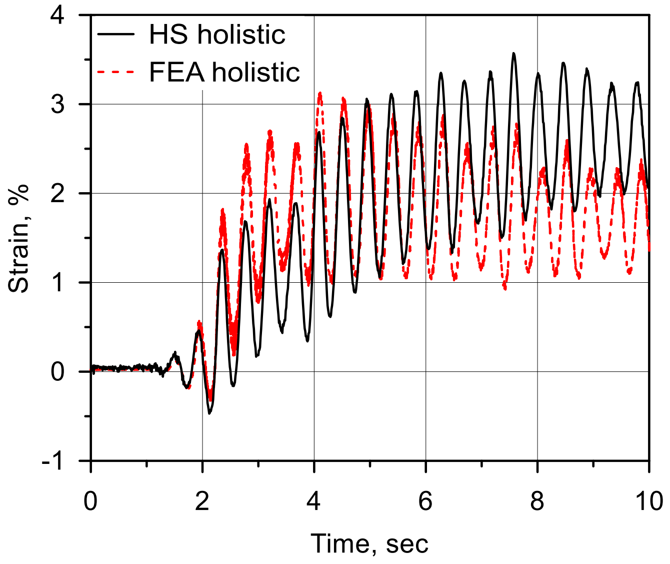

Fig. 11 – Time history plot of Hoop Strain on the elbows from hybrid simulation (HS), at the critical location from numerical predictions (FEA) where maximum hoop strain was observed as they are subjected to closing bending moment.

3.3 Cross-sectional ovalization

Cross-sectional ovalization is quantified and visualised in the form of cross-sectional flattening, i.e. the change of elbow diameter. The horizontal and vertical cross-sectional flattening on the elbow 2 (which is further away from the actuator and the experimental restraint) were compared against the numerical prediction. The experimental result shows a more moderate behaviour of the permanent cross-sectional flattening at vertical direction: at around 2.5s to 3.5s on the time history, the centre line of the *ABAQUS-vertical* curve shifts upward with a magnitude of 5mm, while maintaining a similar level of transient amplitude compared to the hybrid simulation result.

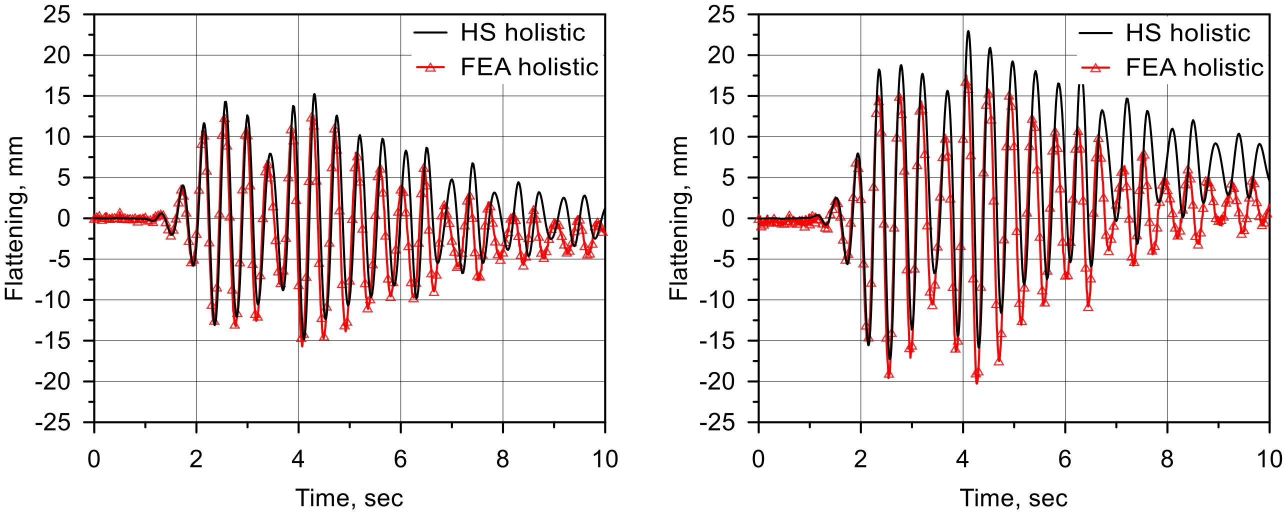

Fig. 12 – Horizontal (left) and vertical (right) cross-sectional flattening-time curves at elbow 2 from hybrid simulation (HS) and ABAQUS numerical prediction (FEA).

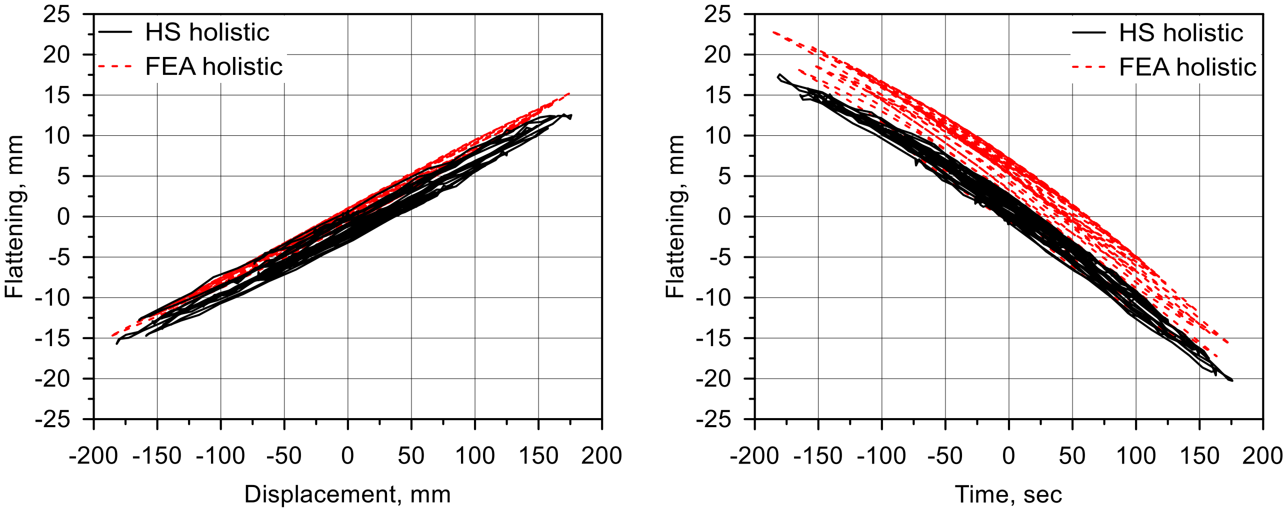

Fig. 13 – Horizontal (left) and vertical (right) cross-sectional flattening-displacement curves at elbow 2 from hybrid simulation (HS) and ABAQUS numerical prediction (FEA).

4. Conclusions

In this paper, the seismic performance of a coupled system which consists of two distinctive industrial structures and a linking NG pipeline within a plant is assessed by means of hybrid simulation. The configuration used for the hybrid simulation setup is explained and the results are discussed. The following observations are drawn from the experiments:

1) Pipe-structure interaction is pronounced in the proposed scenario, which can lead to differential motion at the pipe-ends due to the out-of-phase structural vibration, hence a more significant seismic demand on the elbows. The pipe-structure interaction problem presented herein can be properly addressed by employing hybrid simulation technique.

2) Although the stiffness of pipe is much smaller than that of the supporting structure, test results show a clear coupling effect. In comparison with the behaviour of the two supporting structures with no linking

pipe, the displacement between the supporting structures reduces due to the coupling effect, indicating that the interaction effect between the linking pipeline and the two coupled supporting structures should not be overlooked.

3) An analytical evaluation of the behaviour of the pipe by ABAQUS was well fitted to the results of the hybrid simulation. The analysis results show greater maximum displacement and slightly smaller vibration frequency in comparison with the hybrid simulation results, but it clearly shows the asymmetric hysteretic behaviour of the pipe which is mainly due to the nonlinear geometry of the specimen and the ovalization of the pipe cross-section.

The test results clearly demonstrated that the presence of pipe stiffness is found pronounced such that the interaction effect between the linking pipeline and the two supporting structures should not be overlooked and the hybrid simulation is necessary for capturing the interaction experimentally. The presented hybrid simulation does not account for structural nonlinearity and soil-structure interaction analysis in the numerical substructure module. Efforts should be put into those directions in future studies and more work is needed to account realistically for SSI effects.

5. Acknowledgements

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