



Bolted flange joints equipped with FBG sensors in industrial piping systems subjected to seismic loads

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ABSTRACT

The vulnerability of major-hazard industrial plants to natural hazards has been recognized as an emergent issue whose importance is underlined by the Sendai Framework, established immediately after the Tohoku earthquake of 2011, in Japan. Hence, seismic risk analysis is of paramount importance as testified by the intense research activity that characterized the last years. In this respect, structural health monitoring can represent a valuable tool able to strongly help the decision-making phase. Along this main vein, optical fibers (OFs) represent a class of sensors able to both monitor critical conditions, as leakage of hazardous material, and activate safety barriers, if any. More precisely, optical fibers represent an economic solution, whose characteristics appear particularly suitable for dangerous environments like major-hazard plants. However, investigations relevant to their use for seismic monitoring of chemical/petrochemical plants are rather limited, especially when subject to strong dynamic excitations. As a result, this paper deals with the analysis of optical fiber Bragg gratings (FBGs) applied to bolted flange joints (BFJ) under cyclic loadings. More precisely, two experimental programs, i.e., a cyclic test on a single BFJ and a series of shaking table tests on BFJs of a multicomponent system, demonstrated the effectiveness of the proposed monitoring systems in detecting hazardous conditions and, thus, their potential use in conjunction with safety barriers.

1. Introduction

1.1. Background and motivation

The impact of a natural disaster on a facility storing or processing dangerous substances can result in the release of hazardous substances with possible severe off-site consequences through toxic-release, fire or explosion scenarios. Accidents triggered by a natural hazard, which involve release of dangerous substances are commonly referred to as NaTech events (Krausmann et al., 2017). These include releases from fixed chemical installations and spills from oil and gas pipelines. One of the main problems of NaTech accidents is the simultaneous occurrence of a natural and a technological disaster; both require simultaneous efforts to address a situation where rescue lines designed for disaster mitigation are likely not available, as they may have been damaged by the natural disaster. In addition, hazardous substances releases may occur from single or multiple sources, resulting in multiple chains of

accidents in the same installation, or in different plants; this requires emergency-management resources that can be engaged in responding to the natural disaster in other situations (Caputo et al., 2019).

Despite of a recognized growing of research activities, that results in more strict regulations for the design of industrial activities, NaTech accidents remain an emerging threat (Krausmann et al., 2011). The Directive 2012/18/EU of the European Parliament, implemented by European member states, recognized the relevance of NaTech events. Therefore, Lanzano et al. (2015) presented a large database of earthquake-induced damages for steel and non-steel pipelines. The database can be adopted for the definition of fragility curves commonly implemented for the assessment of Na-Tech risks.

Along this vein, the use of smart sensors-based technology integrated with existing safety sensors, generally present in major-hazard industrial plants can represents an interesting mitigation strategy option. In particular, to reduce the risk in case of major accidents and control the consequences of seismic NaTech events, both the use of *ad hoc*

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monitoring and control systems (Marino et al., 2017) and the implementation of smart technologies -sensors, actuators and innovative systems for seismic protection-can be pursued. For this purpose, various types of sensors can be used, which are often integrated into specific systems for structural monitoring and identification of the release of dangerous substances (Jia et al., 2019; Murvay and Silea, 2012).

Sensors currently available on the market and employable for this purpose, can be broadly divided into: a) sensors for deformation measurements; b) sensors for acceleration measurements; c) sensors for temperature measurements (Ciucci et al., 2019). The first group includes the more traditional sensors, capable of measuring deformation in a point of the structure, also in real time. They are resistive in nature and generally have a high measurement sensitivity. Nonetheless, they exhibit the disadvantage of being installed in specific points of the structure where major deformations are expected; therefore, their installation require a preliminary structural study. Strain gauges and linear potentiometers belong to this family. They generally require a permanent in-situ acquisition system, capable of continuously reading deformations. In the recent past, different experimental tests campaigns demonstrated the reliability of traditional sensors in detecting loss of containment (LoC) events during progression of physical damage (Karamanos et al., 2012; Reza et al., 2014). However, the use of this class of sensors requires a large amount of data to training a trustworthy relation between seismic damage and hazardous material release (Pinheiro da Cruz et al., 2020).

In order to detect the release of hazardous substances through automatic check valves, sensors for acceleration measurements can be usefully employed. They are able to detect both seismic P and S waves and, therefore, they can exploit, the time between the arrival of S and P waves. As a result, they can promptly trigger the actuation systems of safety valves, etc. (Lin et al., 2011). The micro-electro-mechanical-system (MEMS) technology can reduce the costs of these sensors, and nowadays allows to produce accelerometers contained in a single chip. Moreover, these sensors can operate in a wireless environment, e.g. within networks known as radio frequency identification tags (RFIDs), (Pozzi et al., 2011). These systems exhibit a remarkable low battery consumption with a guaranteed life of at least 10 years. These sensors generally provide a favorable integration into early-warning systems; it is well known that early-warning systems exhibit a series of problems related to both signal arrival time and the so-called "false alarms". These issues are still under investigation due to economic losses related to false alarms (Sättele et al., 2015).

An alternative to the aforementioned sensors, which are widely used in chemical industries for leakage detection, is based on temperature measurements associated with substance release (Marić, 2005). Optical fibers belong to this sensor family; they have been often used for releases of dangerous substances in pipes of refineries or in pipelines devoted to the transportation of gas and oil (Inaudi and Walder 2013; Lua et al., 2020). Since these systems are generally continuous, it is not required to determine a specific LoC position in advance, but it is sufficient to install FBGs along the entire line to be monitored (Hou et al., 2014). The cost of optical fibers is rather limited, while the acquisition system is still the most expensive component of the measurement system chain.

For the sake of completeness, we mention other interesting solutions, like the acoustic emission technique (AET), (Ai et al., 2010). The AET represents an important tool employed in non-destructive analysis techniques (NDT), it is commonly used to locate potential cracks in elements subjected to external loads. The sensor is generally based on piezoelectricity and is integrated with a preamplifier. This sensing system can also be implemented with remote sensing techniques by means of wireless technologies. For instance, to monitor cracks in welded piping systems endowed with elbows and tee joints, Sayginer et al. (2020) successfully employed AET.

1.2. Scope

With the objective to examine new industrial facilities endowed with structural sensors to improve safety performance and to upgrade safety conditions of existing industrial plants also retrofitted with sensor solutions, we consider the implementation of smart sensors in view of simultaneous monitoring and control of natural and man-made adverse events. Accordingly, this paper analyzes the feasibility of FBG grating for monitoring and leakage detection of BFJs. For this purpose, two experimental tests have been carried out: i) a cyclic bending test of a full-scale BFJ; ii) a more demanding one, i.e. a shaking table test on a full-scale complex industrial multi-storey frame structure with process equipment and pipes. Both tests demonstrate the feasibility of FBG sensors in leakage detection in structural BFJs, and thus, the potential risk reduction and plant control exerted by these sensors under seismic loading.

In this respect, the paper is subdivided in different sections. In view of a better understanding of piping system and desired goals for a monitoring active system capable to prevent extreme consequences due to hazardous material release under seismic loading, Section 2 focuses on seismic performance of those kind of systems. Section 3 instead, provides an overview of the use of optical fiber sensors and FBGs for seismic monitoring of piping components and BFJs. For the sake of clarity, the cyclic bending tests of the aforementioned BFJ and the relevant experimental investigation is described in Section 4. Conversely, Section 5 introduces a more complex case study based on shaking table tests and the BFJ performance monitored with FBGs. Finally, conclusions are summarized in Section 6 with further perspectives.

2. Related work

With regard to seismic safety of industrial piping systems and LoC detection, we begin underlying that in petrochemical plants, kilometers of pipes are installed to transfer raw and refined materials, e.g., fluid and gas, and connect all components involved in the transformation process, i.e. tanks, distillation columns, furnaces, etc. Consequently, piping systems represent a key element for industrial plants and thus deserve a particular attention, especially in seismic prone-areas where consequences of possible release of hazard materials should be accounted for in view of possible severe hazardous events, like fire, pollution, etc. (Paolacci et al., 2013). The impact of 1999 Turkey earthquake at Itzmit (Sezen and Whittaker 2006) or the 2008 Wenchuan earthquake in China (Krausmann et al., 2010) clearly demonstrated these effects.

The current design approach to piping systems in chemical plants against earthquakes is still strongly based on the allowable design method, instead of the most modern performance-based approach (Bursi et al., 2016). One of the main reasons is the scarcity of information about the definition of limit states for pipes and the structural modeling, which have not yet been treated in a satisfactorily manner. Moreover, most of the seismic Codes and Standards (EN 1998:4 2006; EN13480 2002; ASME B31.3 2004), do not contain enough rules and information for the proper design of industrial piping systems in seismic-prone areas and related consequences due to release of hazardous material, gas or liquid.

As a matter of fact, Eurocode 8 part 4 (EN1998:4 2006), the reference European seismic code for industrial components, is devoted to pipelines, but only of above ground and buried type, which differs from metallic piping systems for many aspects, and thus useless. Actually, the main European contribution to industrial piping systems design is primarily represented by the EN13480, dedicated to metallic piping systems (EN13480 2002); however, the seismic problem is only partially treated and should be more deepened. American know-how on piping systems is instead very rich, especially in terms of design standardization and seismic design calculations, and the long list of Standards and Codes available represents an evident demonstration. More precisely, the main American standard is represented by the ASME B31.3 (ASME B31.3

2004), but many other contributions and guidelines are also available (ALA 2002; ASCE 2011). However, it is necessary to stress that ASME B31.3 does not contain explicit indication on seismic analysis of piping system, but rather refers to the American Standard for the seismic analysis of structures, i.e. ASCE7, which also includes clauses for non-structural elements like pipes (ASCE7, 2010).

In addition to the fuzziness in design rules of piping systems, most of the standards devoted to preventing hazardous material release are inadequate in case of Na-Tech events. In fact, according to literature survey, many of the current common standards for leakage detection are exclusively related to operation conditions and integrity management of pipelines and not to refinery piping systems. Most of them are issued by the American Petroleum Institute (API) and the International Organization for Standardization (ISO) and are mainly focused on technology and in-situ inspections (DNV 2016, API 2017, ISO 2017a/b, ASTM 2017).

The above framework clearly highlights the need of specific techniques to detect leakage in case of extreme events like earthquake. In sum, two main issues are still unresolved: i) a clear methodology for relating seismic damage of piping systems to gas or liquid release; ii) reliable technologies and techniques for leakage detection able to account for severe damage conditions caused by seismic action.

3. Use of optical fibers for seismic monitoring of bolted flange joints

Fiber Bragg Grating (FBG) optical sensors have been installed on several BFJ loaded under different conditions, described in the following sections, to evaluate the seismic behavior of the joints and to monitor any loss of content. The results recorded by the FBG sensors were discussed and compared with those from traditional sensors. In order to better understand working conditions and leakage detection features of FBG optic fiber sensors, a brief overview and possible applications of this technologies in oil and gas industry is provided.

3.1. Characteristics and working conditions of FBG fiber sensors

FBG fiber optic sensors, which are based on interference phenomena caused by the reflection of waves by different parallel crystalline planes, are multifunction transducers capable of detecting, with high accuracy and at long distance, deformations, temperatures, length variations, dynamic pressures, geometry variations and accelerations along a single mode optical fiber bonded or embedded in the structure or on the component to be monitored.

An FBG optic sensor is represented by a diffractive grating photoetched with a UV laser along a single mode optical fiber of 125- μm diameter, whose property is to reflect an associated well-defined light wavelength, generated by a laser or SLED source. The low weight and dimensions of the FBG sensors means a minimal application impact, allowing their installation in the most critical part of a structure.

When the light emitted by a laser source or a super luminescent LED (SLED) passes through the optical fiber, each grating inside reflects the light with a specific wavelength associated with it, expressed in nm (nanometer), which varies according to the length of the grating subjected to traction or compression, induced by thermal or mechanical stress.

Each wavelength variation associated with each individual FBG sensor is detected and converted in real time into temperature, deformation, vibration, pressure or geometry variation, by a dedicated optoelectronic control unit, known as an FBG interrogator.

Therefore, by inscribing along a single mode optical fiber, a certain number of FBG gratings each having its own nominal wavelength, therefore uniquely identifiable, we obtain an FBG fiber optic backbone capable of measuring, in those points where the FBG diffractive gratings are present, temperature, deformation, vibration, pressure or geometry variation.

Furthermore, since their total insensitive to oxidative and erosive phenomena, FBG sensors are able to work in the worst environmental conditions, in a wide temperature range (-180° – 300°), even if immersed in a liquid.

This sensor is suitable for networking since it has a narrowband with a wavelength operating range and hence can be highly multiplexed. This nonconductive sensor can operate in electromagnetically noisy environments without any interference. An FBG sensor is made up of glass which is environmentally more stable and with a really high long-life time. Because of its low transmission loss, the sensor signal can be monitored from longer distances and with a high sensitivity ($\pm 1 \mu\text{e}$ for deformations; $\pm 0.1^{\circ}\text{C}$ for temperatures), making it suitable for remote sensing (Hill and Melts 1997).

Usage of FBG fiber sensors for leakage detection of hazardous equipment in seismic areas.

In order to identify possible applications of FBG fiber sensors, the most frequent seismic damage involving BFJ are here identified. Besides, the most suitable working conditions of these smart sensors are presented.

In the case of unanchored storage tanks, a possible release mechanism can be identified in the junction area between the tank and the inlet and outlet pipes. The lifting mechanism and/or the sliding mechanism of the base, typical of this type of tanks, could in fact cause excessive movement between the tank and the pipes (Fig. 1).

In this case, the movement between tank and pipeline can induce relative rotation between the two flanges of BFJ that can be monitored through an FBG sensor (red line in Fig. 1-(a)). In this way it is possible to identify excessive rotations of the joint and to perform an intervention such as a possible closure of a safety valve or alerting the system for an immediate check of the hazardous condition. Also, FBG temperature sensors could be profitably used for leakage detection as already exploited in the literature (De Bont et al., 2014). Another useful employment of FBG sensors is to incorporate inclinometers in the measurement system to derive the uplift phenomenon and the consequent bending of the pipe, green line in Fig. 1-(a), (Inaudi et al., 2002). Finally, FBG displacement sensors could be used to detect the sliding of the tank base, which could correspond to an excessive axial force in the BFJ, blue line in Fig. 1-(a).

Another type of hazardous equipment widely used in hazardous plants is represented by vertical columns. For this structural archetype, the most sensitive fitting is the BFJ of pipes connected to the vessel at various heights, as well as the pipe typically placed at the top of the column (Fig. 2-(a)). In both cases, the main damage mechanism to be monitored is the relative rotation of the two flanges of BFJ of the column-pipe system. In this respect, FBG strain sensors installed on the pipe flange joint can be profitably used. Indirect measure of the BFJ damage condition could be derived by using FBG inclinometers (Fig. 2-(a)). FBG temperature sensors could be also installed in the most critical BFJs to detect possible leakage.

A similar sensors pattern can be employed for elevated vertical vessels that suffer similar damage conditions. In addition, to avoid serious consequences following the structural collapse, it is always possible to use FBG strain sensors to monitor the yielding and post-yielding condition of the support columns at the base section, where the maximum stress is typically developed (Fig. 2-(b)).

For horizontal pressurized tanks, it may be useful to monitor the relative rotation in the flanges of the connected pipe BFJs (Fig. 2-(c)). FBG strain sensors can also be used to check the stress level in the saddles, due to the oscillation of the vessel under the earthquake.

The above framework clearly shows how the use of FBG sensors can be considered a valuable resource for acquiring useful data and reduce the consequences of a hazardous material release. In fact, the use of sensors for local monitoring of the most sensitive points allows the activation of safety barriers (e.g. shut-off valves) capable of limiting both the leakage of dangerous substances and containing possible domino effects.

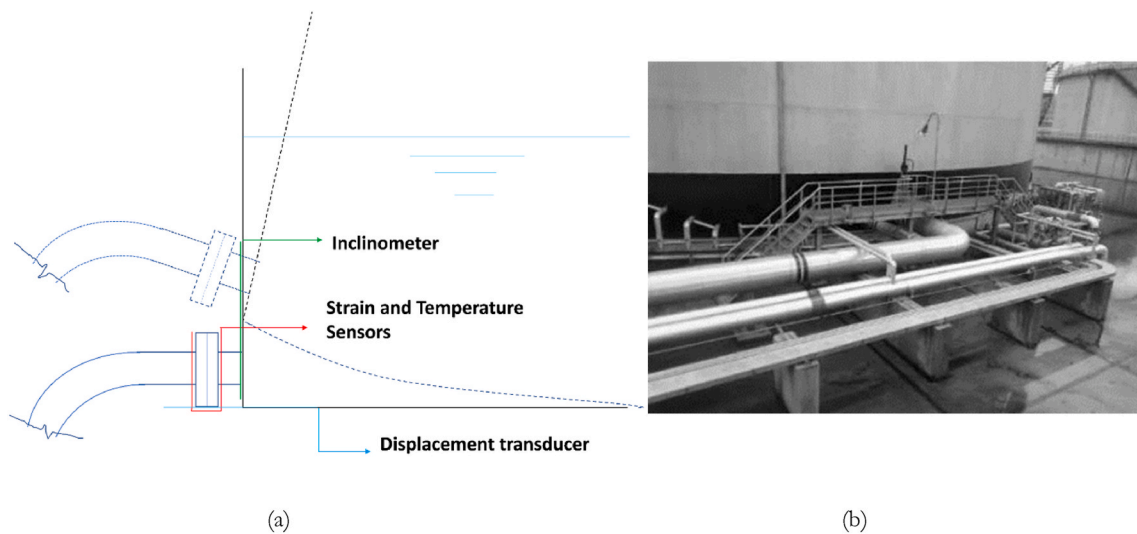


Fig. 1. (a) FBG Sensor placement for the sliding/uplifting monitoring of unanchored storage tanks; (b) example of inlet/outlet pipes of a storage tank.

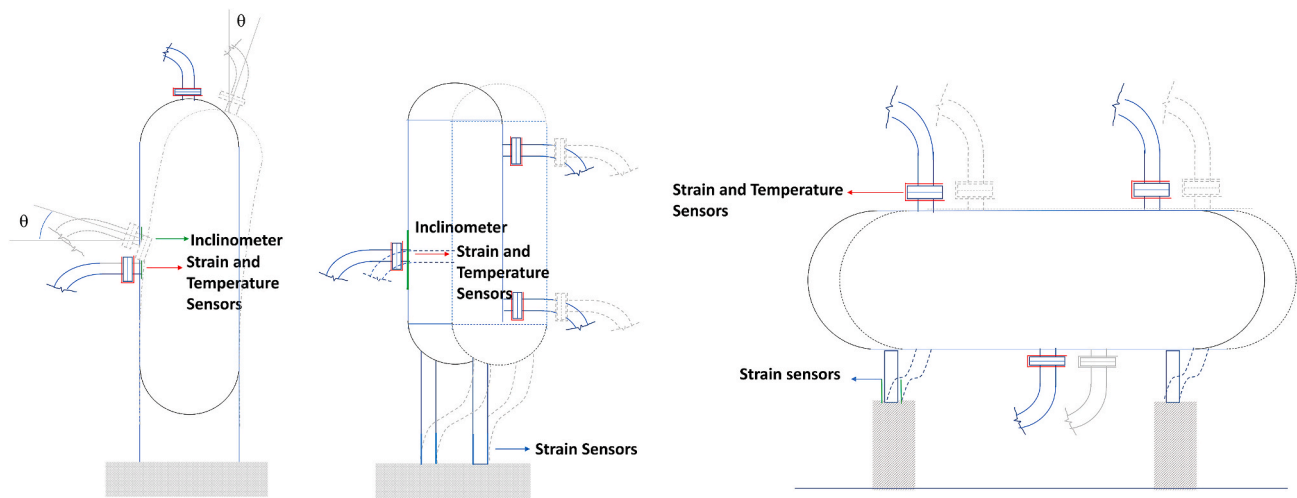


Fig. 2. (a) FBG sensor layout for columns; (b) FBG sensor layout for vertical elevated vessels; (c) FBG layout for horizontal pressure vessels.

In order to show the applicability in practice of FBG sensors for monitoring bolted flange joints subjected to damages involving the release of hazardous material during an earthquake, the results of two different experimental tests will be presented and commented.

4. Experimental investigation on an isolated bolted flange joint

4.1. Description of Case study #1

For the investigation of optical fibers as structural monitoring system and leakage detection of bolted flange joints, two relevant case studies are herein considered.

The first one is composed of a coupled tank-piping system, which employs a smart sensor based on AET technology (Sayginer et al., 2020). In particular, the piping network is made by API 5 L X52 steel, equivalent to the European P355 steel. Besides, it encompasses 8" (outer diameter: 219.08 mm; thickness: 8.18 mm) and 6" (outer diameter: 168.28 mm; thickness: 7.11 mm) schedule 40 pipes. Furthermore, the piping network includes several critical components, mainly two elbows, a bolted flange joint, and a Tee joint. The layout of the piping system and the main dimensions are given in Fig. 3, where the bolted flange joint, considered for the experimental tests, is circled in red. This

joint is considered critical because of the unanchored conditions of the tank that can have some sliding and thus stress in bending and axial conditions of the flanged connection. Details on the bolted joint components are provided in Section 5.

4.2. Description of mock-up and sensors layout

The specimen consists of a portion of piping which also includes a standard flanged joint, designed according to EN 1092-1 (2007), whose gasket has been selected according to EN 1514-2 (2005).

The dimensions of the specimen and flange are shown in Fig. 4. The pipe has a diameter of 219.1 mm, a thickness of 8.18 mm and a total height of 1.608 m. The flange plates have an external diameter of 375 mm and are connected to each other by $\phi 30$ mm bolts and welded to the pipe with welds of adequate strength.

Fig. 5 shows the sensors layout used for the experimental test. It consists of a series of LVDTs for measuring the relative displacements between the two flanges of the joint. There are also strain gauges (SG) to measure both longitudinal and circumferential local deformations.

To measure the horizontal displacements at the top and at the base of the column (sliding), two wire potentiometers have been installed as illustrated in Fig. 5a. Similarly, other two wire potentiometers placed in

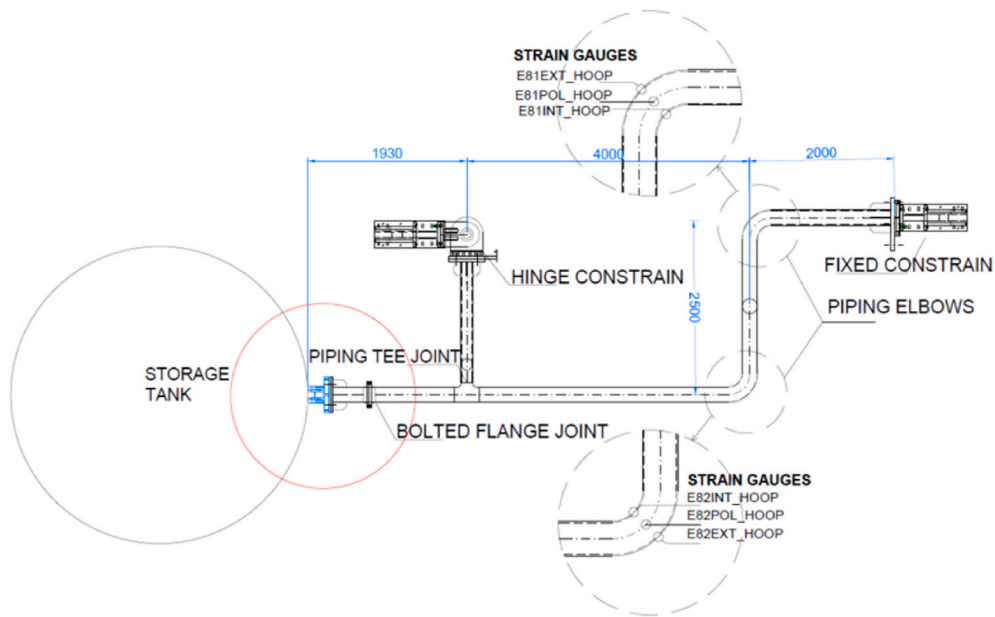


Fig. 3. Case study #1: tank-piping system and secondary components, (After Sayginer et al., 2020).

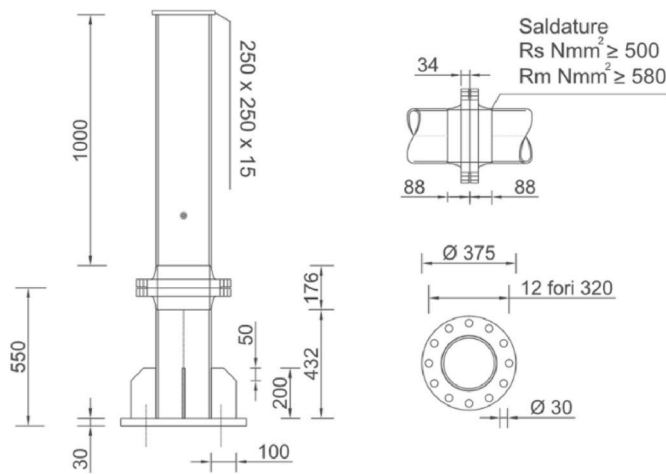


Fig. 4. Main dimensions of specimen and flange joint.

vertical position were used to monitor the vertical displacements of the ground anchor system (to the right and to the left of the specimen) (Fig. 5a). The rotation of the base was calculated as the ratio between the sum of the vertical displacements and the distance between the two potentiometers.

In addition to traditional sensors, a fiber optic sensors system was installed with twofold purpose: a) measuring both the mechanical quantities measured by traditional sensors to validate their reliability (US type of Fig. 5a and b) measuring temperature variations (LD type of Fig. 5a). The latter are generated by pressure variations caused to the Joules Thomson phenomenon (Maric, 2007), which therefore indicate conditions of material release (leakage).

For the application of Fluids Leakage Detection monitoring on the experimental flanged test pipe, one leakage detector has been installed around the two flanges, which is composed by six FBG-based mechanical transducers (US) and four FBG-based thermal transducers (LD), able to detect any leakage caused by a relative rotation of the flanges or by a local failure of the pipe.

The leakage detector fiber optic terminal was then connected to a channel of the interrogator unit, able to read with high accuracy and

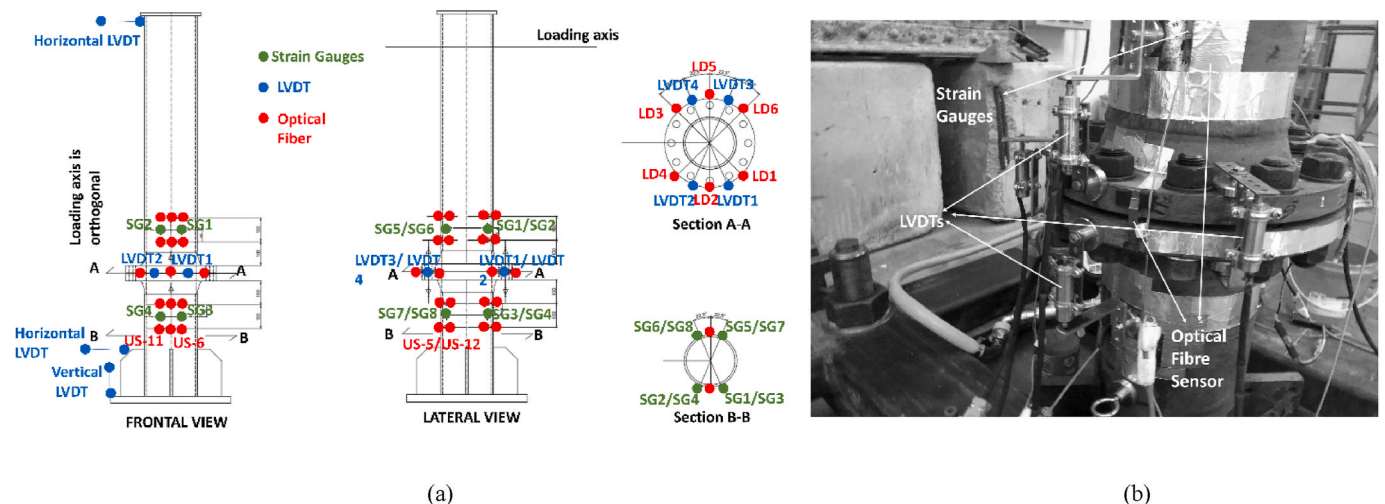


Fig. 5. (a) Sensor layout for the flange monitoring (b) Sensors installed on the specimen.

sensitivity, deformations and temperature variations up to 2.5 kHz sampling rate for each of the FBG sensors installed along the optical fiber. The interrogator unit, thanks to the very low signal loss rate, can be installed at a long distance from the FBG sensors, maintaining accuracy, sensitivity and safety of the measurement.

To validate the system dedicated to leakage detection (LD sensors), a test setup was developed, as shown in Fig. 6, consisting of a support in composite material instrumented with four FBG sensors encapsulated inside a Teflon capillary to ensure the mechanical decoupling of the FBG sensor and allow only thermal sampling.

To test the capacity of the LD sensors to detect leakage, a radial-direction hole was artificially created on the pipe from which the pressurized liquid was instantly released. In Fig. 6-(a) it can be observed the moment when the temperature variation corresponds to the instantaneous loss of the liquid off the hole highlighting the generation of the Joule-Thomson effect (Fig. 6-(b)).

4.3. Description of the test setup

The experimental setup illustrated in Fig. 7a was conceived with the idea of creating a cantilever scheme, fixed at the base and subjected to an imposed displacements history at the top. This has allowed to easily determine step-by-step the static behavior of the structure, also in the nonlinear field, and thus to detect the structural damage.

The displacements history was applied by using a 250 kN MTS hydraulic actuator with a stroke of 25 cm. The characterization of the monotonic behavior of the structure was derived by using a quasi-static displacement history with a velocity equal to 0.02 mm per second. This allowed to follow up the evolution of the local and global response of the structure.

An external access point for the liquid was located at the pipe bottom, (Fig. 7b), and was used for the pressurization of the system pumping water up to the desired pressure level. In the examined case, the maximum applied pressure was equal to 30 bar. To facilitate the pressurization and de-pressurization of the pipe, a water outlet point has been created at the top. This allowed to check the full liquid conditions in the pipe and facilitate the emptying phase after each test. In order to assure fixed conditions at the pipe bottom, a series of steel plates and profiles were used as illustrated in Fig. 7a. However, this system did not guarantee the expected rigid behavior. Consequently, the ground anchorage system was also monitored to derive the rigid horizontal

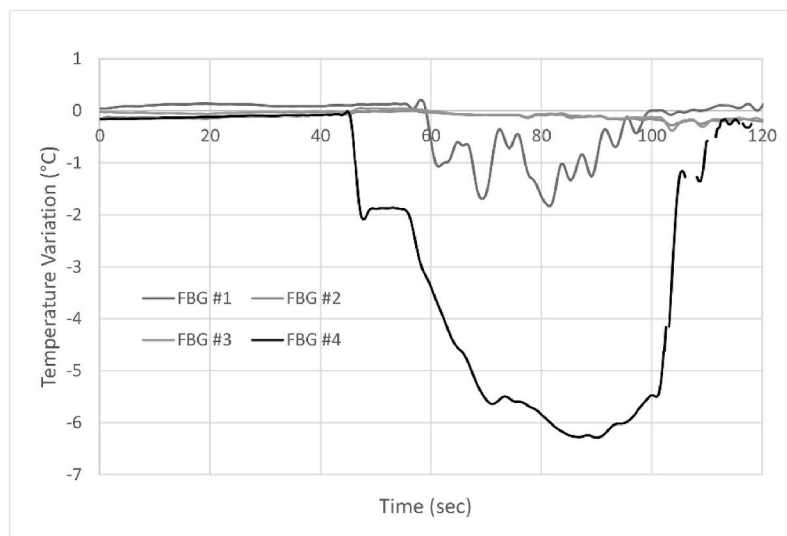
displacement generated, during the test, by the bottom joint rotation. This component was used to derive the net elastic/plastic displacement at the top.

5. Results

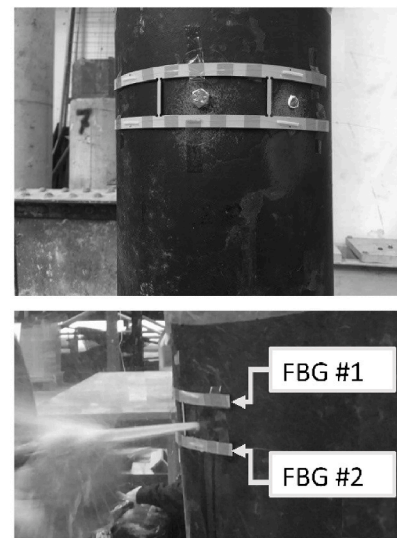
Fig. 8 shows the displacements history with and without the contribution of the rigid displacement of the pipe, where it is possible to observe the finite deformability of ground anchorage system. Fig. 9 illustrates the force-displacement relationship of the pipe. Firstly, it is possible to observe the yielding condition of the pipe, which occurred for a displacement of 42 mm, beyond which the force remained constant, demonstrating the full plasticization of the bottom pipe section. This behavior is confirmed by the local deformations of the pipe measured by the strain-gauges along the longitudinal direction, Fig. 10a. The onset of the yielding conditions occurred for a deformation of 0.2% which corresponds to the yielding conditions of the pipe steel (P355). The force-displacement relationship also shows that at the onset of the liquid release, as demonstrated by the instantaneous drop of the pressure, the pipe was still in the elastic phase.

To better understand the behavior of the flange in both leakage and plasticization conditions, Figs. 10b and 11 show, respectively, the relative displacement and rotation between the two flanges of the joint. Moreover, Fig. 11 shows the corresponding moment-rotation relationship. The relative rotation was defined according to Reza et al. (2014), Section 3.4 Eqns.(1)–(2). In particular, the rotation is defined as the sum of two rotations: the relative rotation between the two flanges and the rotations of the pipe section adjacent to the flange. See Reza et al. (2014) for reference.

The relative rotation corresponding to the leakage condition was equal to 0.015 rad, as shown in Fig. 11, whereas the corresponding moment is about 82.67 kNm. This value is fully compatible with the predictive model proposed by Bursi et al. (2017), Section 4.2 Eqn (8). The referred mechanical model is based on the framework of the EN 1591-1, (2013). More precisely, the model considers the BFJ as composed of three main components: bolts, flanges and gasket. For each component, it evaluates the tensile/compressive forces involved, considering also the resulting forces due to internal pressure and external applied load conditions. Additionally, all these forces are referred to a generic design load condition. However, it is defined as an enhanced model since it takes into account also interactions with shear



(a)



(b)

Fig. 6. a) Joule-Thomson effect during the validation test, b) test setup of the validation test.

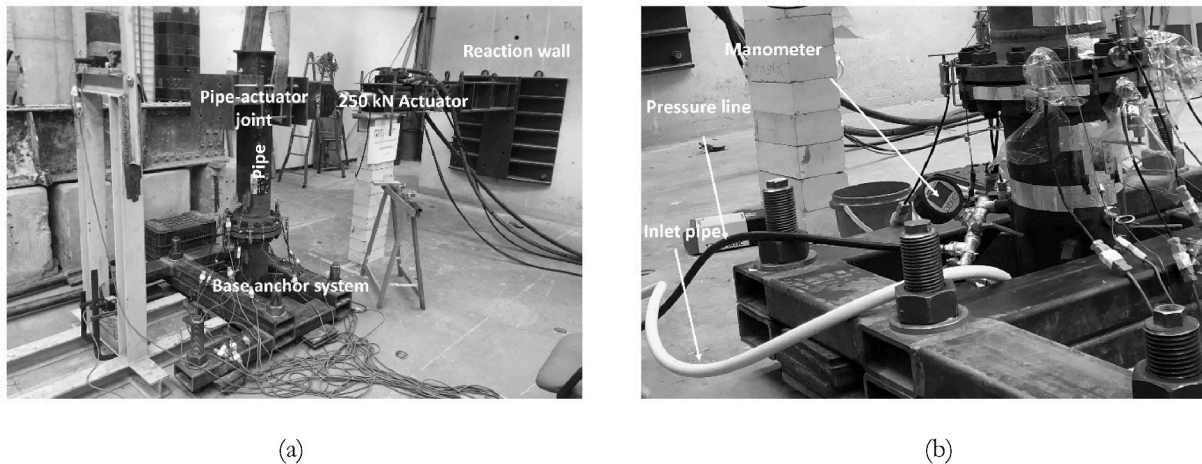


Fig. 7. (a) Experimental setup (b) Liquid pressure system.

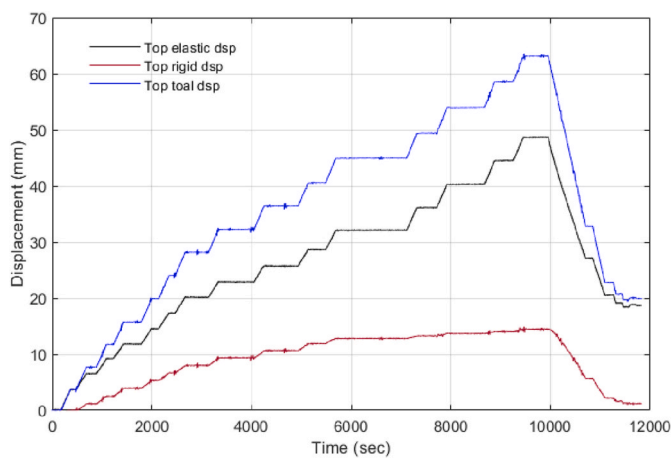


Fig. 8. Top displacements history.

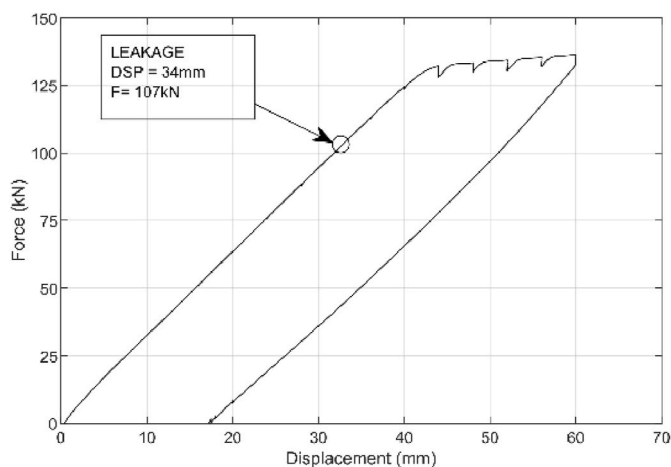


Fig. 9. Force-displacement relationship.

force. Results of its application are shown in Fig. 12. As can be seen the estimated maximum equivalent traction applied to the BFJ is 1038.5 kN, corresponding to an equivalent leakage moment of $M_{leak} = 83.07$ kNm. The experimental data reveals to be in good agreement with the provisions of the analytical model, derived in Section 4.2 of Bursi et al. (2017). In fact, as shown in Fig. 12, the experimental point lies outside

the safety domain for leakage prevention, meaning the occurrence of a leakage scenario.

The results recorded by traditional sensors have been compared with the results recorded by FBG optic fibers system. Fig. 13a and Fig. 13b show, respectively, the deformation and the relative displacement of the flanges. As can be appreciated, the trend of the plot and the values recorded are really close to the value recorded by traditional sensors and shown in Fig. 10a and b. The FBG sensor US-5 have recorded a peak value of deformation of about 4.8 me that are fully comparable with the peak value of 4.2 me recorded by SG4 strain gauge. Similarly, the maximum relative displacement of the flange recorded by LVDT2 is very close to that recorded by the LD-6 FBG sensor, (Fig. 13b).

6. Experimental investigation on bolted flange joints part of an industrial plant substructure

6.1. Description of Case study #2

The second case study regards an industrial multi-storey frame structure with process equipment and pipes, which has been tested in a wide experimental campaign at the Eucentre laboratory in Pavia (Italy), (Butenweg et al., 2020). The full-scale mock-up consists of a primary steel structure supporting several process units, i.e. the secondary elements.

The main structure was conceived as a three-storey steel frame with flexible diaphragms made of crossbeams hinged to the frame beams. Fig. 14 shows some views of the test structure on the shaking table. The structure is 3.7 m × 3.7 m in plan with a storey height of 3.1 m, which leads to a total height of 9.3 m. Two vertical and two horizontal tanks were installed at the first and second floor, respectively. Dimensions of the storage tanks and a schematic of the piping layout, together with some pictures of the flange joints are illustrated in Fig. 15. More details on the structure and the experimental campaign results can be found in Butenweg et al. (2020).

The efficiency and robustness of fiber optical sensors have been tested also during the monitoring of two BFJs during a shaking table campaign performed on a typical industrial plant. The primary steel structure of the tested prototype industrial plant is a three-storey moment resisting frame with flexible diaphragm made of crossbeams.

The piping layout is designed with DN 100 elements with 3.6 mm of thickness. Besides, test structure was equipped with a complex system of sensors which includes FBG fiber optics sensors for leakage detection, strain-gauges SG, LVDT and accelerometers, to study the dynamic behavior of the structure and its dynamic interaction with secondary elements (pipes and tanks). The shaking table test consists in applying an artificial generated accelerogram by increasing the PGA level up to 0.69

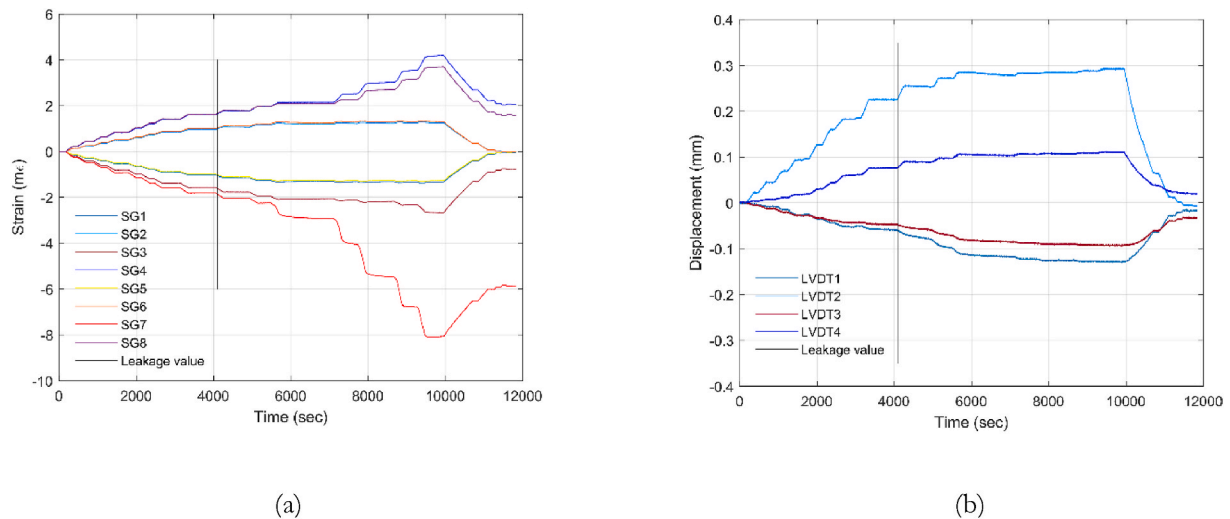


Fig. 10. (a) Deformation evolution measured by strain-gauges (b) Relative displacement histories of the flange joint measured by LVDTs.

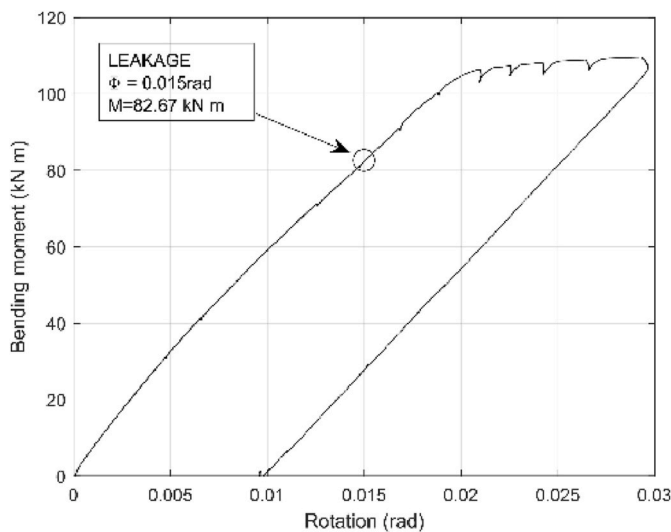


Fig. 11. Moment – Rotation relationship of the BFJ.

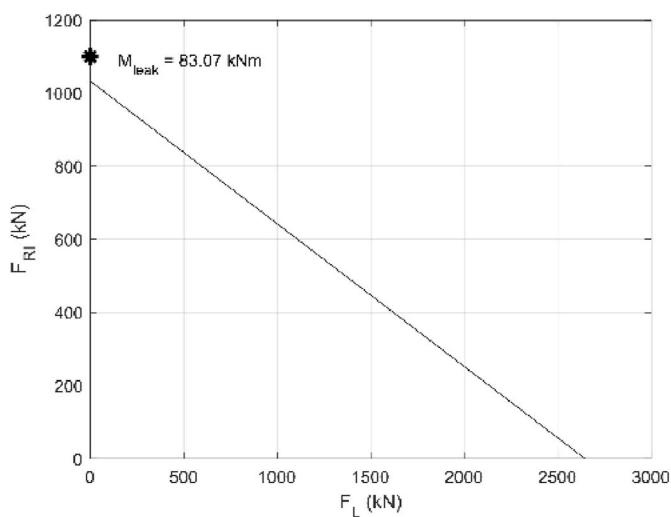


Fig. 12. Leakage domain of the BFJ (after Bursi et al., 2018).

8.

Two critical BFJs (Pos. #4 and Pos. #6, Fig. 15), belonging to a pipe connecting the vertical tanks at first floor to the horizontal tanks at second floor, have been monitored with both optic fibers GS4LD sensors and traditional linear potentiometers, in order to measure the flange opening and detect the leakage during the seismic test. Three SGs and three LVDTs have also been installed around the BFJs at 120° to each other, as shown in Fig. 16, with the aim to evaluate damage conditions of the pipe.

For the application of the optical fibers, a transducer dedicated to monitoring liquid leaks was developed and engineered using both the non-regular coupling of the flanges control method and the measurement of temperature.

The structure of the integrated transducer for GS4LD leakage detection is composed by two semi-sectors in composite material constituting the support on which the optical fiber travels, equipped with 4 FBG strain sensors and 4 FBG temperature sensors.

Taking advantage of the technical and operative metrological features of fiber optic sensors, briefly reported in Section 4, both of the two GS4LD transducers, equipped with n. 8 FBG sensors each, were connected to one of the four channels of the GS4X interrogator positioned 60 m away, without any risk of signal dispersion.

By increasing the sampling of strain sensors up to 2.5 kHz, the GS4LD transducer can also be used for vibration monitoring. Fig. 16b shows the layout of the installed FBG system.

As can be appreciated in Fig. 17a, the T-H function results of the LVDT sensors show a maximum flange opening value equal to 42 μm recorded by LVDT #17. The latter have also recorded a residual plastic deformation corresponding to a displacement of about 7 μm. This confirms the over conservatism of the pipe design for typical industrial pipe-rack, as already demonstrated in (Butenweg et al., 2021). In order to reduce interference from unwanted noise due to power lines or power supply ripple, a finite impulse response (FIR) low-pass filter with cutoff frequency of 30 Hz was applied to recorded signals. In particular, the FIR filter uses a least-squares approximation to compute the filter coefficients and then smooths the impulse response with a Hamming window.

Concerning FBG optical sensors results, while GS4LD-2-S2 and GS4LD-2-S3 have shown results very close to the LVDT sensors in terms of trend and peak value, GS4LD-2-S1 and GS4LD-2-S4 have shown a maximum flange opening value of about 160 μm. In particular, GS4LD-2-S1 have recorded a residual plastic deformation, corresponding to a displacement of about 90 μm in the BFJ, as showed in Fig. 17b. However, no leakage detection has been observed during all the test, as

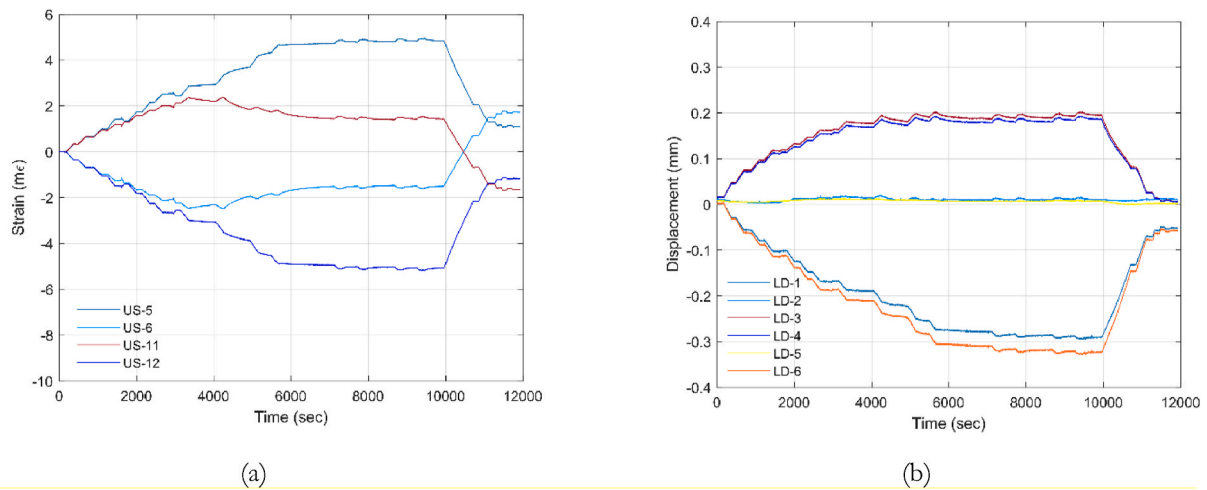


Fig. 13. (a) Deformation measured by FBGs (b) Relative displacements of the flange joint measured by FBGs.

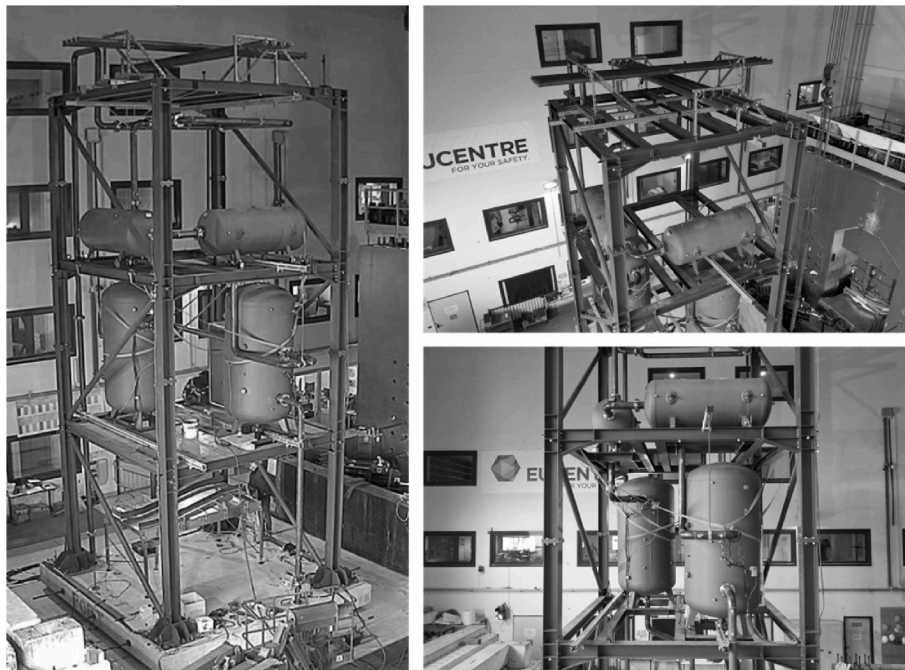


Fig. 14. Case study #2: Mock-up photographs at the EUCENTRE Laboratory (after Butenweg et al., 2020).

confirmed by the data coming from the FBG temperature sensors.

7. Summary and conclusions

The use of FBG optic fibers has been largely recognized to be effective in monitoring civil and industrial structures subjected to seismic loading conditions, thanks to the versatile employment of optical fiber systems both in distributed and localized structural configurations.

Besides, applications in oil and gas industry are rapidly growing. However, exploitation of FBG sensors for monitoring hazardous conditions in Seveso industrial plants is still rather limited. This is mainly due to the scarce and limited experience in managing seismic damage conditions for hazardous plants, with a special attention to the identification of related consequences to both people and environment.

In this respect, two important projects have been recently devoted to these aspects, whose main results were described above. The first one (MSMART) aimed at studying the use of Smart Sensors and, in particular, FBG sensors for the control of disastrous events in major-hazard

industrial plants caused by earthquakes. The second one (SPIF) developed a realistic simulation through seismic shake table tests of an industrial multi-storey steel frame structure endowed with secondary process equipment and pipes.

In view of a full implementation of the EU Seveso III directive, the results of these two tests were used as benchmark for the validation of FBG optical sensors in predicting potentially hazardous events. Both tests were focused on bolted flange joints (BFJs), identified in the literature as particularly vulnerable in terms of loss of containment (LoC) of hazardous material. The following conclusion can be drawn:

- FBG sensors used as traditional sensors for detection of critical strain and stress conditions appears fully credible. In fact, the comparison of the response with long-established sensors, i.e. strain gauges, linear displacement transducers, LVDTs, etc. demonstrated their reliability in monitoring structural quantities of interest.
- FBG sensors can also be profitably used for the assessment of BFJ and, in particular, for leakage detection in seismic conditions. Based

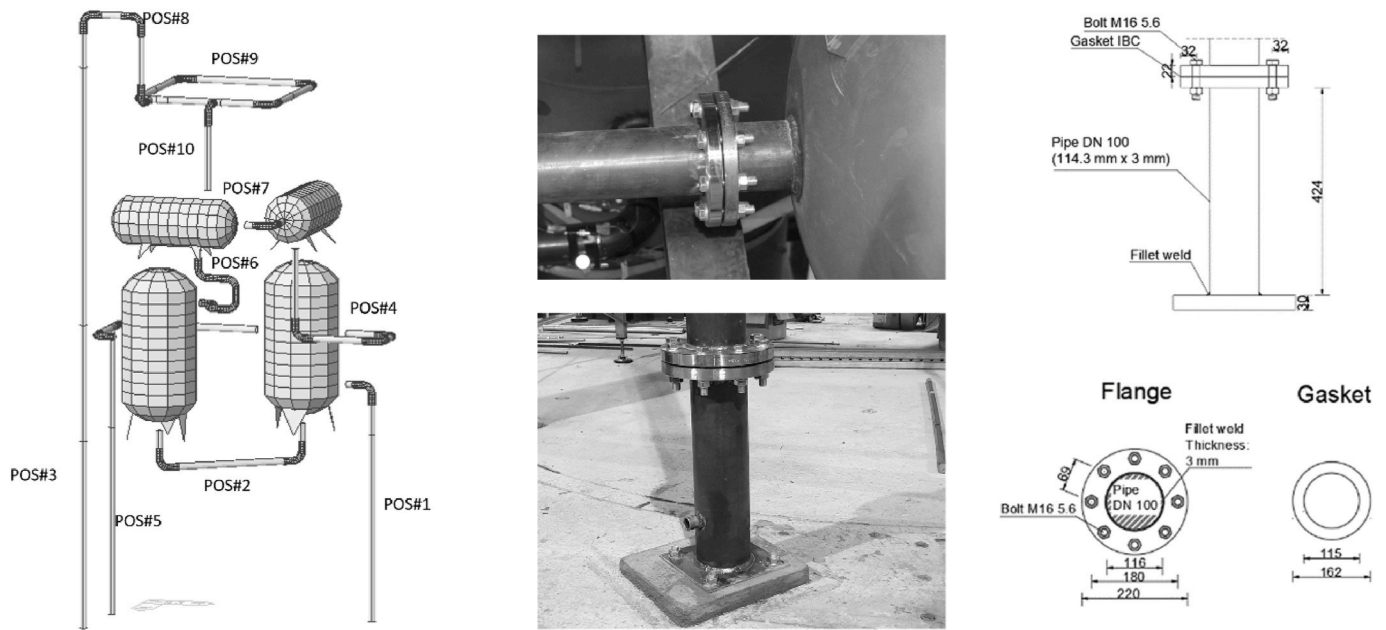
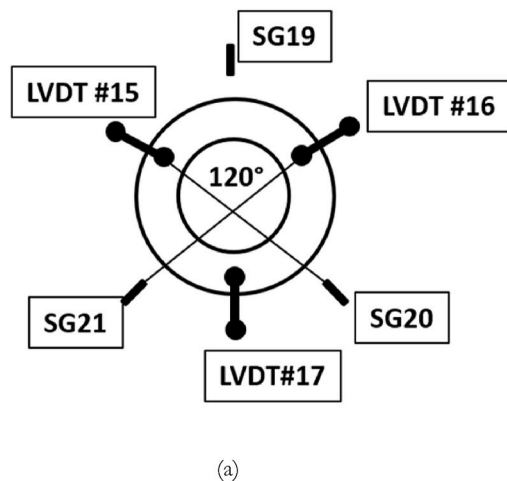
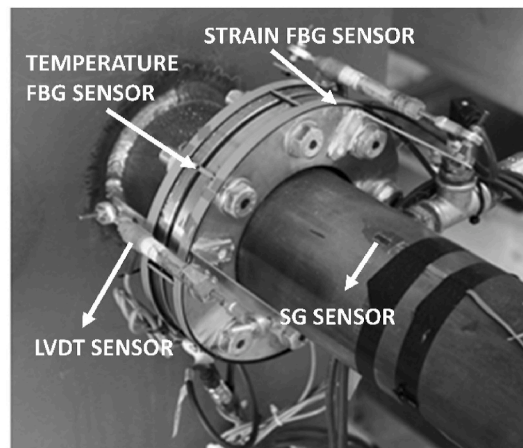


Fig. 15. Piping layout and flange joints details.



(a)



(b)

Fig. 16. (a) Traditional sensors Layout (b) GS4LD optic fibers based Leakage Detection transducer installed on one of the two pressurized vessels mounted on the EUCENTRE shaking platform in Pavia.

on the Joule-Thomson effect, it is always possible to detect LoC events using temperature sensors. The pressure drop due to the LOC event generates a temperature decrease easily detectable by an FBG sensor. The test on a single BFJ fully showed these capabilities.

- The use of FBG optical fiber sensors in monitoring BFJ, also in dynamic conditions, has been tested in a real-scale seismic simulation event on a prototype industrial plant. To the best of authors' knowledge, these experiments represent the first application of FBG sensors in realistic dynamic tests for BFJ monitoring system and leakage detection.
- Simplified installation of FBG sensors on BFJ and possible use of acquisition systems far away from on site condition environment, as demonstrated in the shake table test at EUCENTRE, render the proposed sensor systems especially suitable for hazardous environments, where the interaction with external elements needs to be limited.

Suitable sensor layouts for different equipment have been proposed

based on the experience gained by damage survey after past seismic events. However, given the variety of situations that can be encountered in oil and gas industry, the identification of further advantages and limitations in the use of FBG for structural integrity and LoC of BFJ under seismic conditions requires further studies. Finally, to fully validate the use of FBG-based optical sensors, especially as leakage detectors, additional test programs on BFJ are needed.

Author contribution

Fabrizio Paolacci, Gianluca Quinci and Chiara Nardin dealt with the experimental tests and critically analyzed the results, Marino Alessandra and Mariano Ciucci cured the state of the art and the related works, Valerio Vezzari implemented the FBG system and derived the results.

Declaration of competing interest

The authors declare that they have no known competing financial

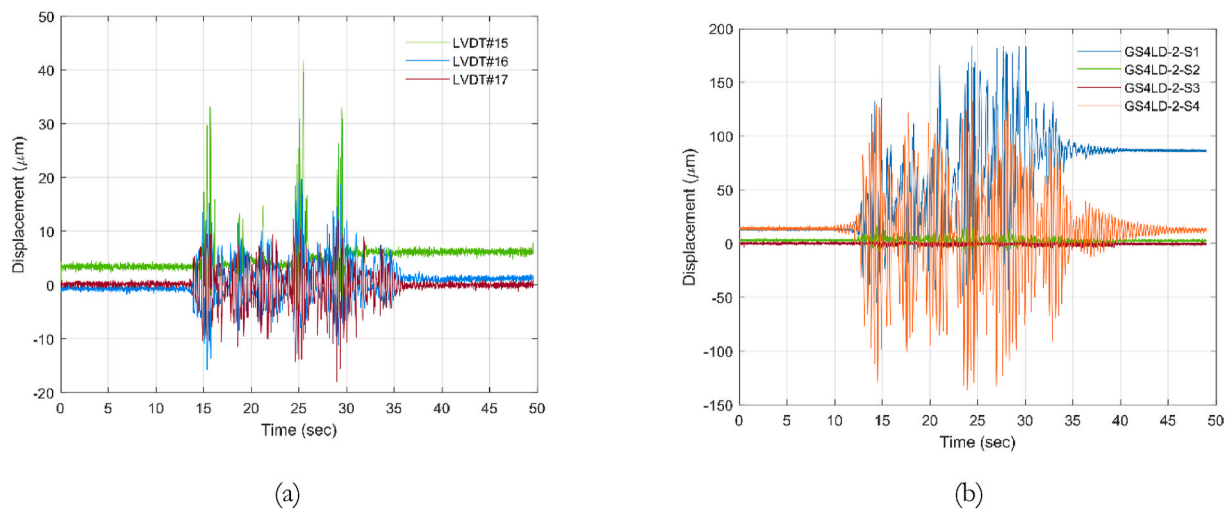


Fig. 17. (a) Time history relations of flange opening recorded by LVDTs (b) Time history relations for flange opening recorded by FBG sensors.

interests or personal relationships that could have appeared to influence the work reported in this paper.

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