Seismic Performance of Bolted Flange Joints in Piping Systems for Oil and Gas Industries

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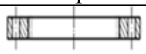
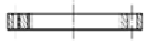
SUMMARY:
Recent seismic events showed a quite high vulnerability of industrial piping systems and components, where damage ranges from simple failure of joints to failure of supporting structures. The performance of the whole piping system strictly depends on the functionality of its individual components. Moreover, the behaviour of bolted joints is complex and critical under seismic actions. Therefore, they need special attention and deep investigation. In addition even for refinery industries, it is also important to know the leakage behaviour of typical flanged joints. Currently, both American and European codes are available to design flanged joints under static loading. Nonetheless, there is no code available to take into account seismic loading effects on these joints. Along these lines, we intend to present in this paper the results of a test campaign on two different types of flanged joints carried out at the University of Trento(Italy), by means of bending and axial loading, respectively. Test results were favourable and were analysed and compared with: 1) the demand provided by piping systems connected to a typical support structure, 2) allowable, yielding and ultimate design values provided by available codes.

Keywords: Piping systems, Bolted flange joints, Seismic design, Experimental test.

1. INTRODUCTION

Currently, available standards for the design of bolted flanged joints (BFJs) e.g., EN1092-1(2007), EN1591-1(2009) and ASME B16.5 (2003) mainly ensure joint integrity and leak tightness under operating conditions. The suggested thicknesses of the standard flanges are high which makes these joints stiff. These standards do not have design rules that take into account seismic events. However, a thinner joint is expected to exhibit potentially better performance under a seismic event compared to a thicker joint because thinner joints dissipate more energy than thicker joints. Experimental results by Nash and Abid (2000) show that flanges with lower weights have advantages over the flanges with higher weights. Moreover, studies made by Touboul et al. (1999, 2006) and Huang (2007) demonstrate that seismic demands are not very high in piping systems and a very high level of seismic input is required to introduce damage to the components of piping systems. Hence, under most of the earthquakes, even a thinner flanged joint could perform equally well. Along this line, the University of Trento (UNITN) designed two non-standard thinner flanged joints based on structural Eurocode EN 1993-1-8 (2005) rules in order to assess their performance under real operating conditions. A comparison of thicknesses between a standard and the non-standard flanges under the same design conditions is presented in Table 1.1.

Table 1.1. Comparison of thicknesses between a standard and non-standard flanges

Standard plate flange (EN 1092)	Non-standard plate flanges (designed by UNITN)	
 Plate Flange Thickness- 36 mm	 Plate Flange (Design 01) Thickness- 18 mm	 Plate Flange (Design 02) Thickness- 27 mm

2. DESIGN OF NON-STANDARD BOLTED FLANGED JOINTS

Two different thinner flanged joints were tested. Except the thicknesses, all other dimensions of the designed flanges are the same as those of a PN 40 (for a DN 200 pipe size) plate flange given in the Eurocode EN 1092-1(2007). The given thickness of this standard flange is 36 mm whereas the thicknesses of the designed non-standard flanges are taken as 18 mm (Design 01) and 27 mm (Design 02) respectively. The thicknesses are chosen according to the failure modes 1 and 2 of the Eurocode EN 1993-1-8 (2005). A Matlab code to check the designs of these thinner joints according to the Eurocode EN 1591-1(2009) was properly designed. One of the joints (Design 02) satisfies the Eurocode EN 1591-1(2009) while the other (Design 01) does not. Grade 355 steel was used both for the pipes and flanges, bolts were of 8.8 grade and spiral wound type gaskets were chosen. The designed flanges and their dimensions are presented in Fig. 2.1 and Table 2.1. The two test specimens are shown in Fig.2.1(c). The bolts were tightened according to ASME PCC-1(2010).

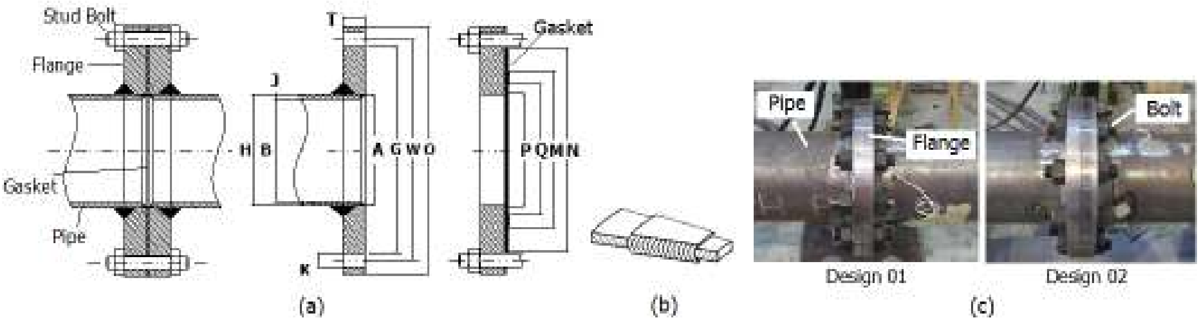


Figure 2.1. (a) Designed bolted flange joint with dimensions; (b) spiral wound gasket; (c) actual test specimens

Table 2.1. Dimensions of the Designed Non-standard Bolted Flange Joints

Pipe Size	O	W	G	K	T	J	A	B	H	P	Q	M	N	No of Bolts	Stud Bolt Size
DN 200 SCH 40	375	320	290	30	18 (Design 01) 27 (Design 02)	8.18	221.5	202.74	219.1	216	228	248	290	12	M 27 x 3.00

2.2 Test Program and Loading Protocol

Eight experimental tests on bolted flange joints were performed by UNITN. The test program is presented in Table 2.2.

Table 2.2. Test Program on Bolted Flange Joints Performed by UNITN

Test No.	Test name	Test type	Description of the test
Test 01	BSML18	Bending	Monotonic Bending of Design 01 (18 mm thickness) Flanged Joint
Test 02	BSML27	Bending	Monotonic Bending of Design 02 (27 mm thickness) Flanged Joint
Test 03	BSCL18	Bending	Cyclic Bending of Design 01 (18 mm thickness) Flanged Joint
Test 04	BSCL27	Bending	Cyclic Bending of Design 02 (27 mm thickness) Flanged Joint
Test 05	ASML18	Axial	Monotonic Axial of Design 01 (18 mm thickness) Flanged Joint
Test 06	ASCL18	Axial	Cyclic Axial of Design 01 (18 mm thickness) Flanged Joint
Test 07	ASCL27	Axial	Cyclic Axial of Design 02 (27 mm thickness) Flanged Joint
Test 08	ASCL27	Axial	Cyclic Axial of Design 02 (27 mm thickness) Flanged Joint

2.3 Instrumentation

For both of the bending and axial tests, strain gauges were mounted in the same positions of the pipes. In order to have an estimation of the stresses generated in the welded sections of the pipes, strain gauges, S1, S2, S3, S4, S7 and S8 were placed according to the recommendations for the assessment of structural hot spot given in Hobbacher (2008) and Zhao et al. (2001). Strain gauges S5 and S6 were placed at a distance equal to half of the diameter of the pipe since this region retains the plastic deformation of the pipe. The placements of strain gauges are presented in Fig. 2.2.

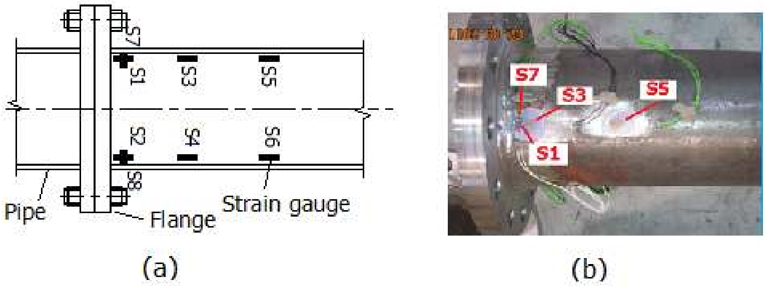


Figure 2.2. (a) Placements of strain gauges; (b) strain gauges mounted on the test specimen

A total of twelve displacement transducers and two inclinometers were used in the bending tests as shown in Fig. 2.3(a). Total rotation of the joint is calculated as the sum of the rotation of the flanges (measured by the two inclinometers) and the rotation of the pipe (measured by the transducers E, F, I and J). The difference of the displacements between E and I, divided by their mutual distance, gives the rotation of the pipe in one direction, while the difference of the displacements between F and J gives, in the similar manner, the rotation of the pipe in the other direction. Sum of these two values give the total pipe rotation. The definition of rotation is presented in Fig. 2.4(a).

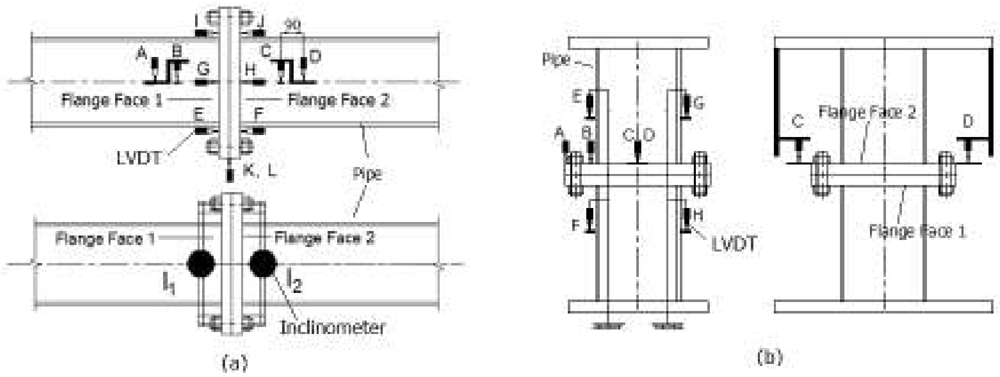


Figure 2.3. Instrumentation for (a) bending tests; (b) axial tests

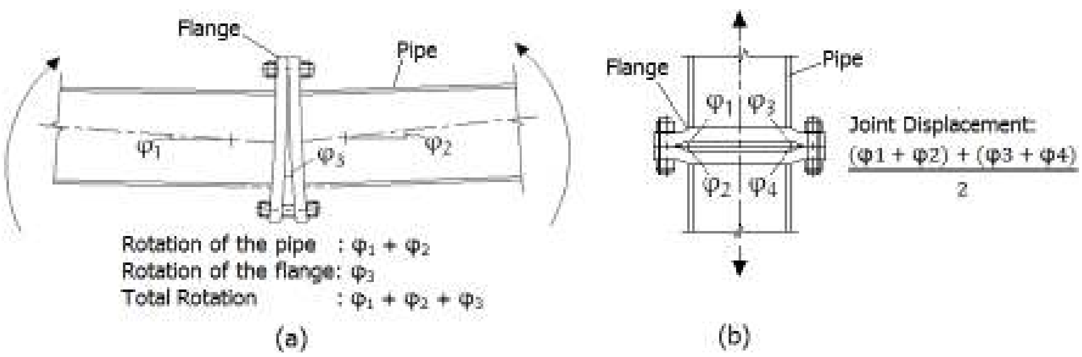


Figure 2.4. Definition of (a) total rotation in bending load, (b) joint displacement in axial load

A total of eight displacement transducers were used in the axial tests as shown in Figure 2.3(b). Total displacement of the system is measured by the transducers A, B, E, F, G, and H. Each of the differences of displacements between E and F, between G and H and between A and B, gives the displacement of the joint separately. The average of these values is assumed as the joint displacement. The definition of joint displacement is presented in Fig. 2.4(b).

2.4 Test Set-ups

A single 1000 kN actuator was employed for the bending tests while two 1000 kN actuators were used for the axial tests. A sketch and the actual test set-ups are shown in Fig. 2.5 and Fig. 2.6.

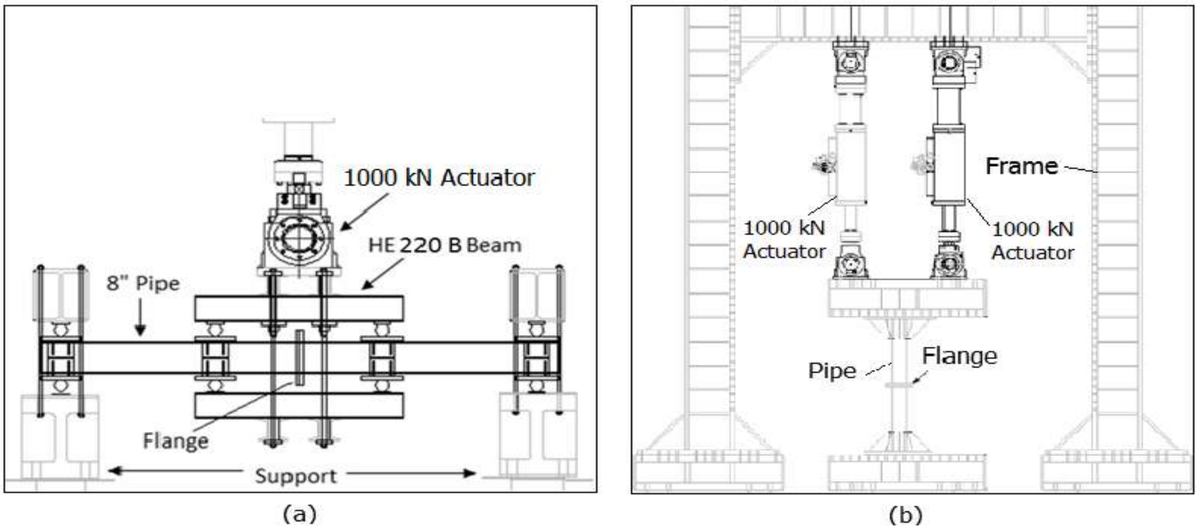


Figure 2.5. Test set-up for (a) bending tests; (b) axial tests

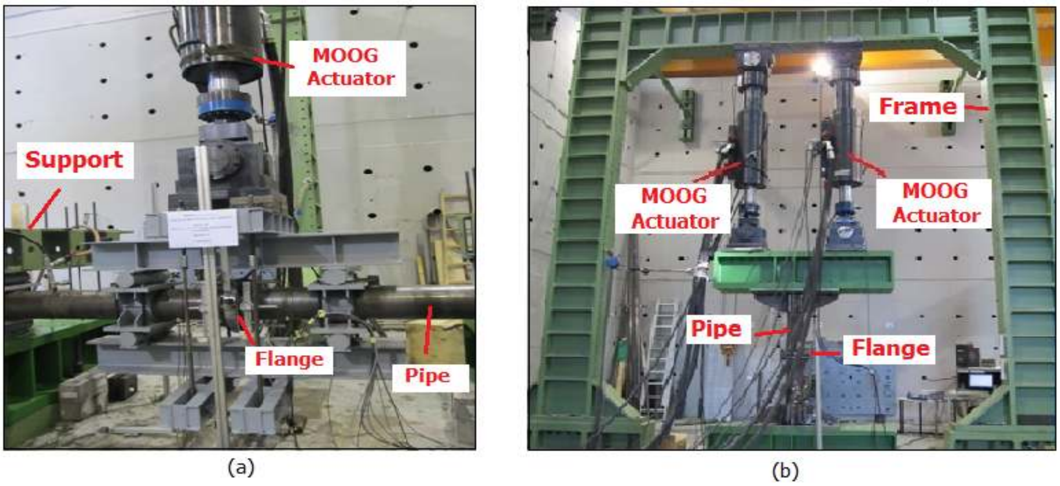
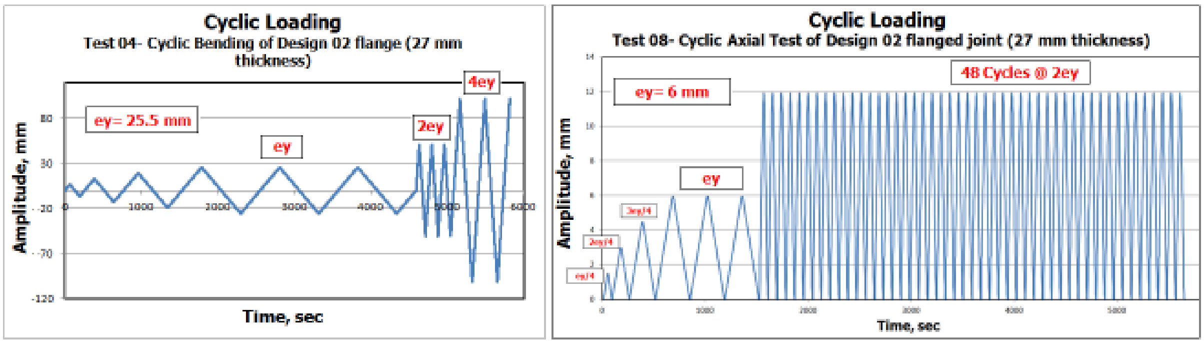


Figure 2.6. Actual test set-up for (a) bending tests; (b) axial tests

2.5 Loading protocols and pressure level

The loadings for the tests were chosen according to ECCS 45 (1986) loading protocols. Two MOOG actuators with the capacity of 1000 kN were used to apply load on the specimens. A pressure of 1.5 MPa was used for all the tests. Twelve cycles were required during the cyclic bending tests to fail the pipe, while 54 positive cycles were used in the axial tests. The cyclic loading protocols for a bending and an axial test are shown in Fig. 2.7.

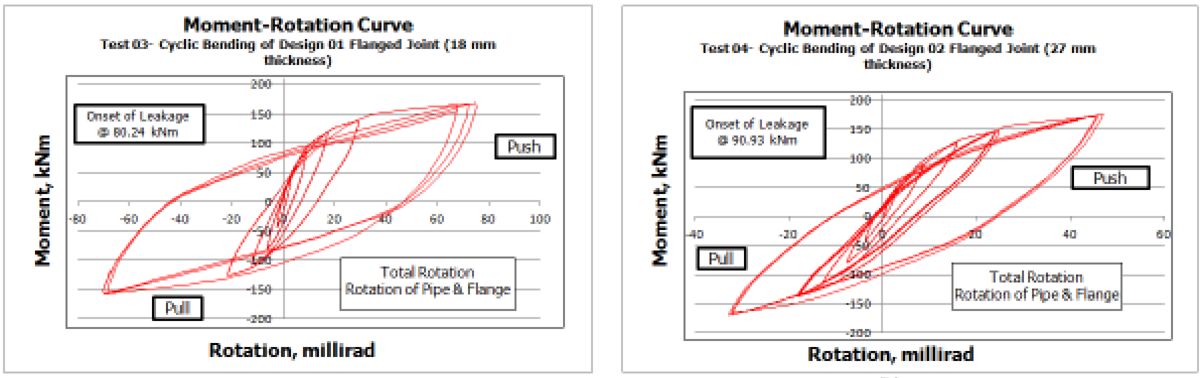


(a) (b)

Figure 2.7. ECCS loading protocols used in (a) a bending test (test 04); (b) an axial test (test 08)

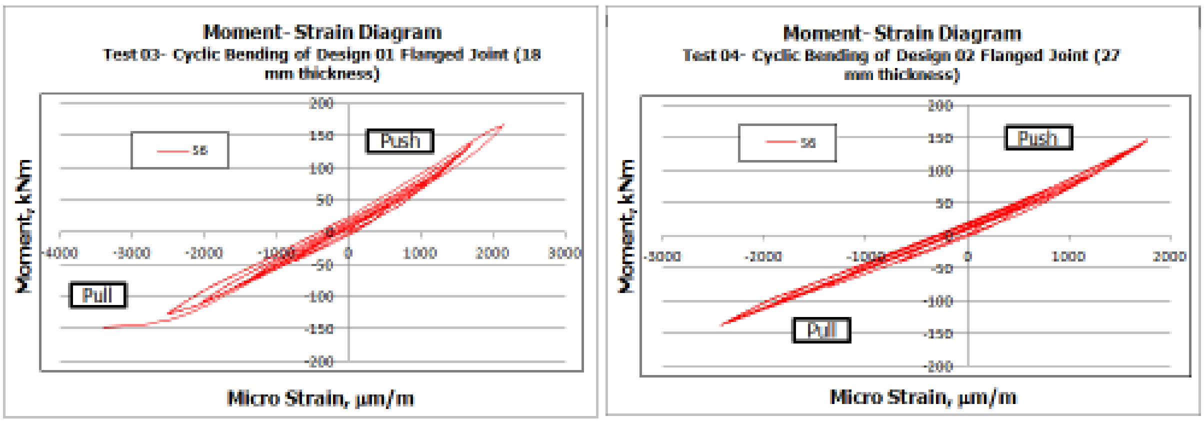
3. TEST RESULTS AND OBSERVATIONS

Both of the designed flanged joints showed good behaviour under axial and bending loadings. The leakage moments and loads were well above the allowable moments and loads for pipes suggested by different American and European standards, i.e. EN 13480-3 (2002), ASME B31.1 (2001) and ASME 31.3 (2006). None of the flanged joints failed during the tests. The moment-rotation diagrams of Design 01 and Design 02 joints under cyclic bending loadings are presented in Fig. 3.1. It can be seen that both of the joints show good non-linear behaviour and are capable of dissipating energy while cycling with limited rotation and high level of load.



(a) (b)

Figure 3.1. Moment-rotation curves of (a) Design 01 joint and (b) Design 02 joint under cyclic bending loadings



(a) (b)

Figure 3.2. Moment-strain curve of strain gauge S6 of (a) Design 01 joint and (b) Design 02 joint under cyclic bending loadings.

Moreover, as expected, Design 02 joint shows stiffer behaviour than Design 01 joint. However, the pipe wall exceeds its yield strain (2053 micro strain for the considered pipe) during the tests. The moment-strain diagrams of the strain gauge S6 of test 03 and test 04 are presented in Fig. 3.2. The joints also showed good performance during the axial tests. Small amount of deformations were found with high level of loads and leakage loads were well above the allowable limits suggested by standards EN 13480-3 (2002), ASME B31.1 (2001) and ASME 31.3 (2006). The load-displacement diagrams of Design 01 and Design 02 joints under cyclic axial loadings are presented in Fig. 3.3. The strain levels in the pipes were below the yield limit as can be seen from Fig. 3.4.

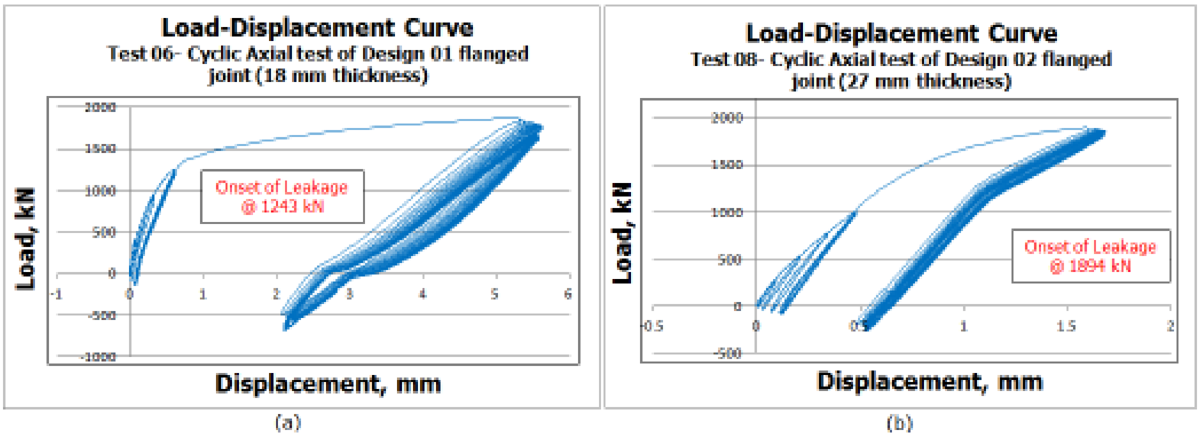


Figure 3.3. Load-displacement curves of (a) Design 01 joint and (b) Design 02 joint under cyclic axial loadings

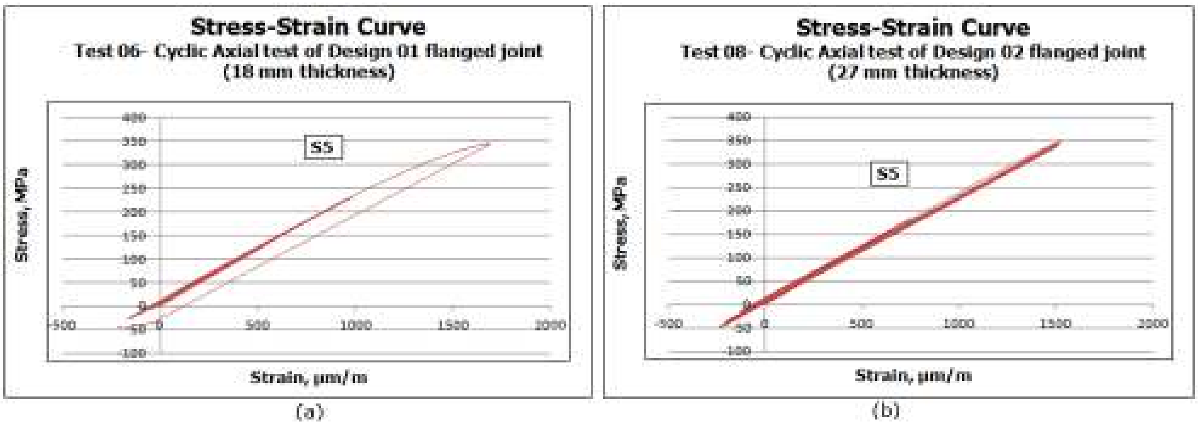


Figure 3.4. Axial stress-strain curve of the strain gauge S5 of (a) Design 01 joint and (b) Design 02

During the bending tests, failure occurred in the pipe near the welding region of the joint where buckling was also found. However, no failure occurred in the pipe or in the joints during the axial tests with a maximum load of 2000 kN, which was the limit load of the two actuators used. A list of observations on different components of the joints and the leakage loads after relevant tests are presented in Table 3.1 while photos of some components are shown in Fig. 3.5.

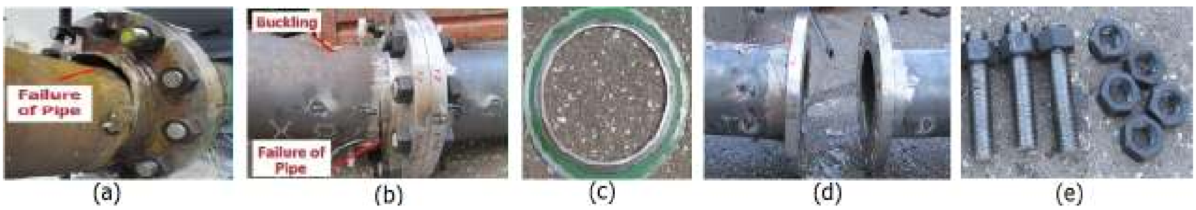


Figure 3.5. Observations of some components after relevant tests: (a) pipe failure (test 03); (b) pipe failure and buckling (test 04); (c) deformed gasket (test 04); (d) flange faces (test 08); (e) bolts (test 07)

Table 3.1. Leakage loads and observations of different components of flanged joints after relevant tests

Test	Leakage Load	Observations				
		Pipe	Flange	Gasket	Bolts	Welding
BSML18	99 kNm	Buckling near the joint	Small deformation	Plastic deformation	Small bending	No deformation
BSML27	106 kNm	Buckling near the joint	Very small deformation	Plastic deformation	Small bending	No deformation
BSCL18	80.24 kNm	Buckling and failure of pipe near the joint	Small deformation	Plastic deformation	Small bending	No deformation
BSCL27	90.93 kNm	Buckling and failure of pipe near the joint	Very small deformation	Plastic deformation	Small bending	No deformation
ASML18	1170 kN	No deformation	Very small deformation	Small deformation	Small bending	No deformation
ASCL18	1243 kN	No deformation	Very small deformation	Small deformation	Small bending	No deformation
ASCL27	1812 kN	No deformation	Very small deformation	Small deformation	Small bending	No deformation
ASCL27	1894 kN	No deformation	Very small deformation	Small deformation	Small bending	No deformation

4. COMPARISON OF DEMAND AND CAPACITY OF THE JOINTS UNDER INVESTIGATION

4.1 Seismic response of a typical industrial piping system

The piping system here analysed belongs to a refinery, whose plan view is shown in Fig. 4.1(a). The support steel structure is composed of seven transverse moment resisting frames placed every 6 m, realized with commercial HEA/B steel profiles. In the longitudinal direction it behaves like a truss structure, which is reinforced with 6 braces. Horizontal bracings are also installed to avoid excessive relative displacements between the pipe supports. The piping system presents a typical piping layout with pipes having different diameters. To simplify the analysis, only the structural contribution of 8'' pipes has been considered, whose layout is shown in Fig. 4.1(b). The remaining pipes are considered only as weight. Several flanged elbows are present within the pipe-rack and at both the ends of the piping system.

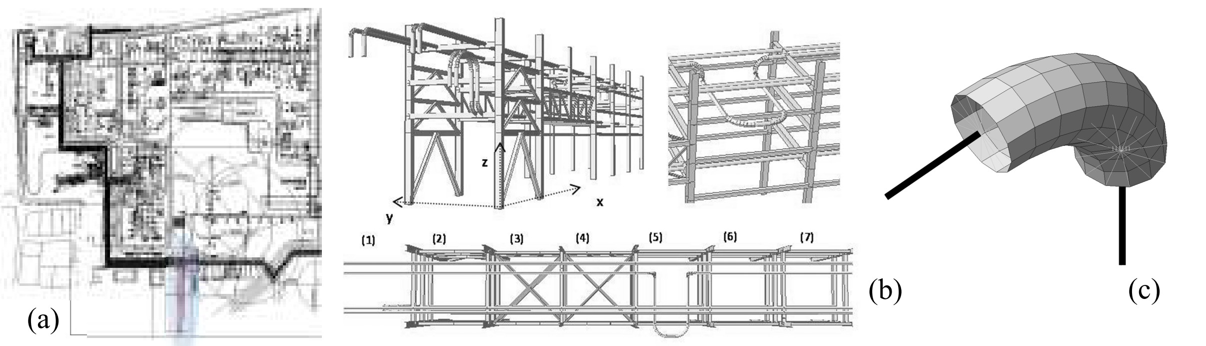


Figure 4.1. (a) Plan view of the refinery**;** (b) The piping system; (c) Shell FEM for the elbows.

Pipes may contain several fluids, such as, Amine, cooling water and high to medium pressure steam. The vertical loads corresponding to the weight of the pipes, insulation and fluid are considered as uniformly distributed equal to 12 kN/m. The main characteristics of the piping system are: i) Structural steel S-275 JR, ii) pipe steel A106 Grade B, iii) pipes with diameter of 8'', iv) pressure of the pipes 0.5÷5 MPa, v) Temperature range 47 °C ÷360 °C, vi) Importance factor I_p=1.5, vi) PGA=0.24 g, viii)

Soil conditions D. The model of the piping systems is illustrated in Figure 4.1(b). Inelastic fiber beam elements were used for the frames, whereas linear truss elements were used for the vertical and horizontal bracing. According to the 25% weight rule suggested by the ASCE07-05, in the analysed the dynamic interaction between the rack and the pipe case cannot be neglected. Therefore, the contemporary presence of rack and pipe is here considered. The pipe is modelled using linear beam element for the straight parts of pipe and by using shell elements to better simulate the behaviour of the elbows (De Grassi and Hofmayer 2005). The analysed piping presents quite stiff support systems, modelled as elastic spring in the transverse direction (Y), leaving free the relative displacements in longitudinal direction (X) and using fix restraints conditions in vertical direction. Moreover, as usual, all the rotations between pipe and pipe-rack have been unrestrained. More details on the model can be found in Paolacci et al (2011).

Both European and American standards assume the following two types of analysis, mandatory for the pipes: (a) Movements due to inertia effects, (b) Differential movement of the supports (within the supporting structure or between adjacent pipe-racks). The first type of analysis is essentially related to the effects of the absolute acceleration on the pipe mass. The second one is due to the relative movements between two supports, within the supporting structure or belonging to adjacent structures. Often the relevant effects are due to the displacement effect rather than acceleration effects. Concerning the case study, the entire model here considered (pipe + pipe-rack) allow identifying both the effects. At this purpose non-linear dynamic analysis has been performed using a set of 7 accelerograms compatible with the EC8 spectrum for Soil B (Figure 4.2) and selected according to a Magnitude range 6-7, a distance from the epicentre < 30 km, and a PGA g in the range 0.25-0.35 g. These parameters are referred to the Operating Basis Earthquake (OBE) condition, for which after the seismic event the operating conditions of the plant can be still assured (Paolacci et al 2011).

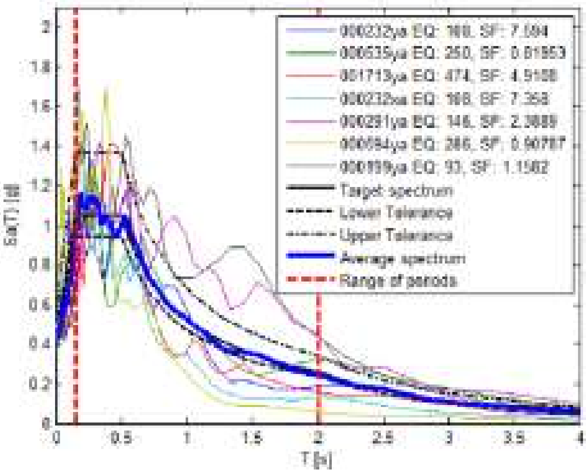


Figure 4.2. Elastic spectra of accelerograms.

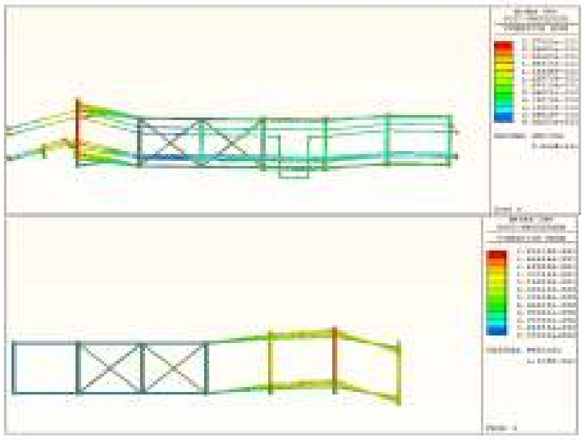


Figure 4.3. Main vibration mode with and w/o pipes.

The modal analysis on the entire system allowed to highlight the important role of the pipes in realizing structural coupling between the several frames of the pipe-rack. For example in Fig. 4.3 the vibration modes of the rack with and without the pipes is shown. The period of the first mode of the rack with and without pipes is similar, whereas the excited mass is higher in the first case, showing the coupling effect of the transverse frames due to the pipes.

The results in terms of moments along the local axes y and z of the pipe are reported in Table 4.1. The resultant moment M_R of the single moments along local axes y and z, calculated according to the EN13480:3 and ASME B31.3 are also shown. The maximum moment is found near the left edge of the rack (bay 2), even if similar values are also obtained within bay 6 and 7.
In addition, the maximum stress level of the pipe in the same points has been also calculated according to the Eq. 4.1, where *SFI* is the stress intensification factor (equal to one for straight pipes) (EN13480 2002), M_A and M_B are the resultant force for dead loads and the earthquake respectively, *p* is the

internal pressure, *D*, *t* and *Z* are respectively the diameter, the thickness and the Inertia modulus of the pipe.

Table 4.1. Maximum bending moment and tension in the pipes

Bay / Moment	1	2	3	4	5	6	7
$\mathbf{M_y}$ (kNm)	1.56	6.91	5.98	4.94	5.04	3.47	2.50
$\mathbf{M_z}$ (kNm)	13.72	15.30	14.15	7.01	8.75	15.84	15.84
$\mathbf{M_R}$ (kNm)	13.81	16.79	15.36	8.58	10.10	16.22	16.04
Tension (MPa)	76.71	86.41	81.76	59.67	64.62	84.54	83.96

$$\sigma = \frac{pD}{4t} + 0.75 \times SFI\,\frac{M_A + M_B}{Z} \qquad (4.1)$$

As clearly shown in Table 4.1 and in more detail in the next section, these results are extremely conservative. This is not a novelty. Studies have shown that the present standards for piping system design under seismic loads are over conservative and modifications have been proposed to relax this over conservatism (Blay et al. 1997, Touboul et al. 1999, Toboul et al. 2006).

4.2 Assessment of the performance of Bolted Flanged Joints

In order to assess the performance of the proposed BFJs, for brevity, a comparison between test results of joints, i.e., leakage loads, and allowable strengths suggested by American and European standards EN 13480-3 (2002), ASME B31.1 (2001) and ASME 31.3 (2006) are made. To calculate the allowable moments and loads under an occasional earthquake, the equation given in section 104.8.2 of ASME B 31.1 (2001), and in section 12.3.3 of EN 13480-3 (2002) are used. The appropriate factor for the earthquake is taken from ASME 31.3 (2006) for the ASME equation. Moreover, a comparison is also made between the test results and the results of the case study already presented in section 4.1. The demand-capacity comparison is presented in Table 4.2, Table 4.3 and Table 4.4. It can be easily found that the leakage loads are well above the allowable design loads and loads demanded by the earthquake.

Table 4.2. Comparison between experimental leakage moment and allowable moments suggested by codes

Experimental moment	**Allowable moments by codes**	
Minimum leakage moment obtained from bending tests	EN 13480, 2002	ASME B31.1 & B31.3
80.24 kNm	51.23 kNm	57.08 kNm

Table 4.3. Comparison between experimental leakage load and allowable loads suggested by codes

Experimental load	**Allowable loads by codes**	
Minimum leakage load obtained from axial tests	EN 13480, 2002	ASME B31.1 & B31.3
1170 kN	885.20 kN	885.20 kN

Table 4.4. Maximum moment, axial force and shear force obtained from the case study

Maximum moment in the piping system obtained from the case study	**Maximum axial force in the piping system obtained from the case study**	**Maximum shear force in the piping system obtained from the case study**
16.79 kNm	180.5 kN	5.08 kN

5. CONCLUSIONS

The highly conservative design of piping systems, as shown in this paper, seems to be in contrast with the modern performance based-design approach, for which a certain level of yielding in the structure is admitted according to a specific performance. The experimental campaign described in the paper and performed by the University of Trento in order to evaluate the cyclic behavior of flanged joints, provided useful information for the design of flanged joints in a more optimal way. In addition, useful information to link the capacity and the demand for several limit states are provided. The experimental results show very favourable performances of the designed bolted flange joints. The joints are capable of dissipating high level of energy without failure; leakage loads were well above allowable loads and loads found from the case study. Therefore, these types of joints can be used in piping systems operating both under normal conditions and under seismic events. To complete the investigation, the performance of the aforementioned flanged joints under higher operating pressure should be investigated.

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