American Journal of Applied Sciences 5 (11): 1448-1460, 2008
ISSN 1546-9239

Experimental Modeling of Pile-Leg Interaction in Jacket Type Offshore Platforms Cyclic Inelastic Behavior

[1]M.R.Honarvar, [2]M.R.Bahaari and [3]B.Asgarian
[1]Marine Structures, Faculty of Engineering, University of Tehran, Tehran, Iran
[2]Faculty of Engineering, University of Tehran, Tehran, Iran
[3]K.N.Toosi university of Technology, Tehran, Iran

Abstract: Offshore platforms in seismically active areas should be designed to survive in the event of severe ground excitations with no global structural failure. The annulus between the pile and leg in jacket-type offshore platforms can be filled with cement grout as a means of reducing horizontal deflections, inhibiting corrosion and preventing local damages. This paper discusses an experimental approach which can be used to demonstrate the effect of grouting on enhanced structural performance of jackets. In this regard, the lateral load bearing behavior of grouted and un-grouted jackets are investigated experimentally with special attention to effect of grout on pile-leg interaction. Results are presented on the cyclic inelastic behavior of two scaled frame models of a representative platform which was recently installed in the Persian Gulf. The objective of this effort was to improve the understanding of the behavior of jackets subjected to lateral motions and specially the effects of exact real pile-leg interaction. it should be noted that this paper addresses the exact and realistic pile-leg interaction. It is concluded that grouting can not be considered as a definite method of improving strength and structural nonlinear dynamic behavior. Although it generally increases the lateral stiffness, but some side effects and points are to be considered. In this paper, the two separate lateral load bearing mechanisms -namely portal (braced) mechanism and frame bending mechanism- are distinguished and the effect of grout on each one is shown.

Key words: Jacket, offshore, platform, grout, cyclic, experimental

INTRODUCTION

General: Most of the jackets have foundation piles through each main leg which are welded to the structure at deck level. Modeling the cyclic inelastic behavior of legs and braces is of utmost importance in any nonlinear dynamic analysis of offshore jackets. In the past years, considerable investigative efforts have focused on understanding the inelastic behavior of offshore structures subjected to severe seismic loadings and numerical methods for predicting this behavior have been developed[15]. Numerical efforts on frame behavior used to be evaluated by experimental tests which were all conducted in a simplified condition without modeling the pile above seabed and pile-leg structural interaction.

In this study, two scaled 2Dimenional models of a platform are fabricated and tested under cyclic deck displacement to show the effect of pile-leg interaction in inelastic range of deformation. Furthermore the different behavioral aspects of grouted and un-grouted pile-leg interaction are investigated.

Where a structure's piles pass through the legs, the primary pile/structure connection is typically made by welding the pile to the structure and/or by grouting the leg/pile annulus. In this case, the pile leg acts as a composite member. In case of un-grouted leg-piles, the effect of shim plates at elevation of horizontal braces have to be considered[10].

Background and scope: Zayas *et al.*[14] reported the results of a series of axial cyclic tests on isolated struts representing typical tubular braces in offshore platforms. Zayas *et al.*[15], reported the experiments on two one-sixth scale models of an X-braced tubular steel offshore platform subjected to cyclic displacements simulating the effects of severe earthquake ground motions. These efforts were numerically studied by Keyvani[11] and Asgarian[4]. Ray Clough and Yousof Ghanaat[8] have studied the dynamic elastic and inelastic behavior of one 5/48 scaled model of an X-

Corresponding Author: B.Asgarian, Assistant Professor of Civil Engineering, K.N.Toosi university of Technology, Tehran, Iran, Phone Number: 00989121253874

braced offshore platform made of tubular members. In this platform, a 5/8 scaled model of the jacket tested by Zayas *et al*. was represented. Earthquake motions used for jacket shaking were modified records using El Centro and Taft recording earthquakes. Linear and nonlinear analyses of the structure on the shaking table were performed using fiber Beam-Column post-buckling element by Asgarian[3].

In this study, a complementary test is conducted in line with Zayas *et al*. efforts[15] to model the pile-leg real interaction through the connection joint and shim-plates and show the effect of grouting in lateral cyclic behavior of offshore jacket type structures.

The experimental program and the frame models employed are described in section 2 of this paper. Two types of frames, representing the current practices are investigated. In one model, the gap between pile and leg is filled with grout, which is called Grouted frame and the other frame is called Un-grouted. The overall behavior of the experimental model is discussed in section 3 of this paper. Particular attention is paid to the effect of grouting on the deterioration of strength and energy dissipation capacity.

Jacket members behavior in nonlinear range of deformation

Portals: Portals are members with essentially constant axial force and variable lateral displacement[11]. The portal behavior of a jacket leg under lateral forces results in a relatively small bending moment at the mid-height of the leg segment between any two adjacent horizontal bracing levels. Grouted and Un-grouted portals behave differently and have different methods of modeling[10].

Struts: Struts are essentially bracing members with constant lateral loads (usually zero) but variable axial displacement[11]. Since jacket braces are connected to legs, which normally have much larger flexural stiffness, their axial response is their most important behavioral characteristic.

Quasi-static loading approach: A good approach to verify specific aspects of the numerical model, as was utilized here, is to impose quasi-static load or deformation histories on the specimen. This type of study provides valuable information on force-deflection relationship of the frame as a whole and also on individual members. Realistic numerical modeling of these loops is essential for accurate computer simulation of the inelastic dynamic response of a structure. Past research on braced frames has been also mostly performed in a quasi-static manner[15]. If it is desired to obtain information to develop and verify numerical models which can subsequently be used to predict dynamic behavior, it is not necessary to perform tests dynamically, because:

- Once a numerical model is verified on the basis of experimental data under cyclic loading, time history dynamic analysis can be used with confidence to check ductility demand, the structural displacements and the energy dissipation of the structure[15]
- Earthquake excitations are non-deterministic and several records must be applied to assess the nonlinear structural response properly[15]
- When the results from specimens with different details (e.g. with and without grout) are being compared, a quasi-static test is to be used in which the same displacement history is imposed on all specimens. If a shaking table test is performed, each specimen will have a different period and therefore is expected to behave differently. Thus, it is not clear whether the differences are due to the details. However, if a dynamic analysis model is being calibrated to a single or several tests, then a shaking table test is better. In a quasi-static test nearly any reasonable numerical model will give hysteretic loops that look perfect, however, they may give different dynamic results

Objectives: While there have been great strides in nonlinear dynamic analyses and these are generally essential to the design and evaluation of offshore and other onshore structures, the programs need to be verified for particular applications and models calibrated to the particular situation at hand. That is, the computer models are only as good as their underlying assumptions. Many aspects of structure behavior are quite complex. These include local buckling, fracture and in this case, aspects of composite behavior. The results of the composite behavior of the jacket legs with the pile-grout, jacket interface is likely to be very difficult to model numerically. Thus, it seems that a realistic nonlinear analysis models will be very complex and it will be difficult to trust its results unless there is experimental verification and perhaps simpler models might be adequate for the particular type of structure being employed. As such, one or more tests are essential to substantiate the nonlinear analyses.

This study presents results of experimental research on steel offshore-type braced frames subjected to large cyclic inelastic loadings, applied in a quasi-static manner, simulating severe earthquake excitations. Two models (fabricated on the basis of a one twelfth scale of a recently installed jacket in Persian Gulf, one in grouted and one in un-grouted condition) were tested. The specific objectives of this investigation are as follow:[15]

- Obtain experimental data on the pile-leg interaction in a correctly scaled model of jacket type offshore structures as similar as possible to the real condition, by considering the connection joints, pile through the leg, crown shim-plates, shim plates at the elevation of horizontal braces, grouting in the gap between pile and leg and etc.
- To assess the effect of grouting on the cyclic inelastic response of tubular steel structures
- Provide observations and information pertinent to the inelastic behavior of X-Braced offshore structures under cyclic seismic-type excitations, applied in a quasi-static manner
- Obtain experimental data suitable for assessing the reliability of numerical procedures used to predict inelastic seismic behavior of frames of the type used for offshore structures

MATERIALS AND METHODS

To achieve the objectives of this investigation, two one-twelfth scale models of a recently designed and installed jacket in Persian Gulf, were simplified, adjusted according to available pipes and laboratory facilities, constructed and tested under lateral quasi-static displacement-controlled histories representative of severe motions. This platform had already been designed in accordance with API criteria, therefore the design of test frames consisted of simplifying the structure to facilitate testing, determining an appropriate scale factor and detailing the specimen frames to avoid undesirable behavioral modes.

Frames configuration: Both frames are quite similar except that, one is grouted in the gap between pile and leg but the other one is not.

The test frames were simplified and consistent with the objectives of the investigation. Therefore only a planar (2D) row was tested. The effect of horizontal braces in the prototype, perpendicular to the modeled face was considered as lateral (out of plane) constraints on legs. The stiffness and weight of the well-head deck was simulated by a box-section beam. Pin connections were employed at bottom of the extended pile. Hydrodynamic forces were not simulated. Considering above mentioned criteria and all limitations in fabrication and test laboratory, frames were detailed as shown in Fig. 1, 2 for jackets, piles and decks and the assemblage, respectively.

Material behavior: Figure 3, 4 and Table 1, present the stress-strain curves for the steel and grout materials used.

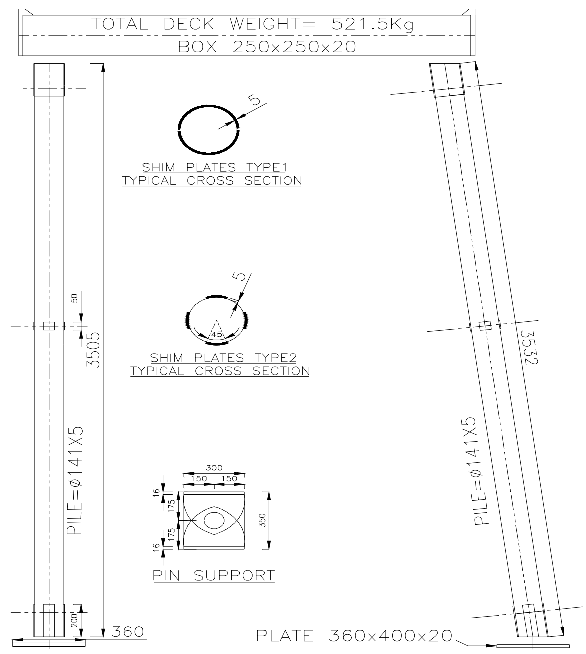

Fig. 1: Pile and deck fabrication drawing

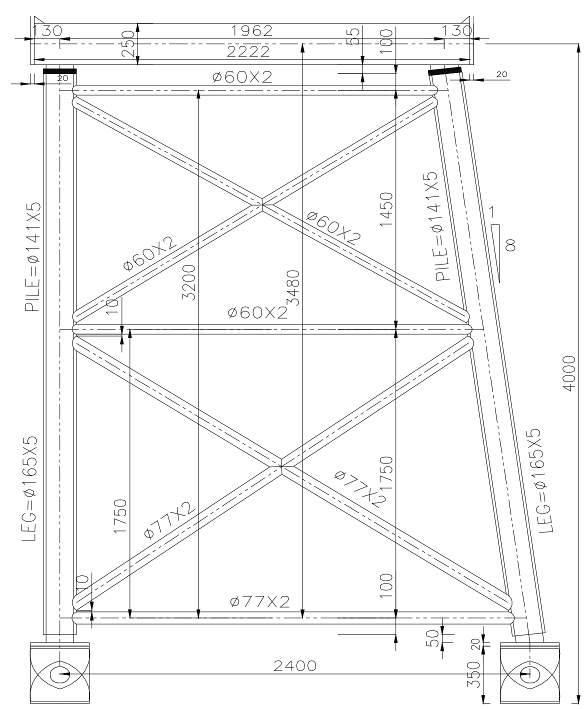

Fig. 2: Platform assemblage shop drawing

Table 1: Pipes material characteristics, tensile test results

Measured result of tensile strength test in lab

Fy (Mpa)	Fu (Mpa)	Elongation	Fy (Mpa) Avg	Fu (Mpa) Avg	Elongation Avg
Brace					
333	437	0.35	342	429	0.313
353	420	0.33			
359	443	0.29			
323	414	0.28			
X Brace joint can					
310	397	0.10	310 (Minimum)	397 (Minimum)	0.1 (Minimum)
350	442	0.16			
Portal					
277	346	0.38	276	327	0.390
284	322	0.41			
283	320	0.38			
260	318	0.39			

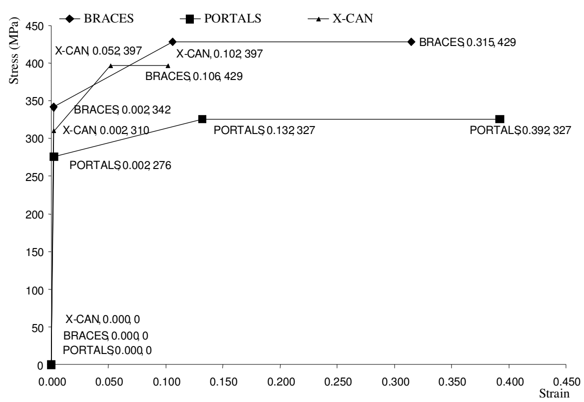

Fig. 3: Pipes material stress-strain curves, tensile test Results

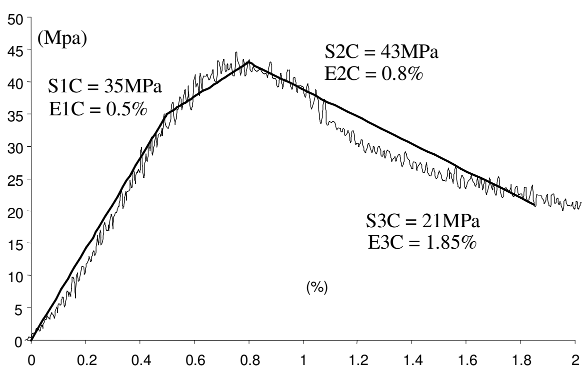

Fig. 4: Average resulted stress-strain curve of 4 grout samples and adjusted curve in drain software

Steel material behavior: Figure 3 and Table 1, show stress strain behavior of the pipes used for the specimen frames. Totally 8 samples were tested (4 for braces and 4 for portals). Two samples were tested for each size of used pipes.

X-bracing joint-can behavior: In this test, the behavior of braces was not focused on, but the portal behavior (both while working with braces and while working individually in bending) and the effect of grout on overall behavior were to be highlighted, therefore joint cans intentionally were not fabricated and the brittle failure (tearing) has occurred because of the Heat Affected Zone area which was developed while 2mm thickness pipes were being welded to each other. However the stress-strain curve of the can was derived by fabricating similar X connections and testing two specimens. The worst of resulted stress-strain curves is presented in Fig. 3 and Table 1.

Grouting material behavior: Some sample cubes ($5\times5\times5$ Cm^3) of grout were tested under compression[10]. The grout was made of seawater and cement type II (with Water/Cement weight ratio of 39% and 1.98 t/m^3 density). Three of the cubes were cured in the wet normal open condition, while other three in the entrapped close condition to simulate the entrapped gap space between the pile and leg where no air circulation would exist. The samples were tested in the MTS machine after 28days. Two of incomplete cured and two of normal cured samples were tested. In real condition, the grout is neither completely entrapped, nor normally can be cured, therefore an average of the tests and the equivalent linear curve are plotted in Fig. 4.

Fabrication: The specimen frames were constructed by qualified fitters and welders who all were engaged and quite experienced in real-scale jackets fabrication. Care was taken to insure proper alignment, minimize initial eccentricities, bevel the ends of members similar to API recommendations, specify close fit-up of welded components and use full penetration butt welds at all tubular member connections. The SMAW electrodes were E6013. All weldments were tested under PT (liquid penetrant examination) and MT (magnetic particle examination), NDT tests and the repairs were done to detect and remove the flaws that could cause premature failure[15].

The welded shim plates on the piles are shown in Fig. 5. After the construction of separate items (Jackets, piles, shim plates, base plates and deck box), they were assembled to each other for both the frames. The connections of top and bottom of piles are shown in Fig. 6 and 8. After the completion of the frames, one was grouted in the gap between pile and leg using exactly the material and mix ratio mentioned above,

Fig. 5: Assemblage of shim plates on piles at mid-horizontal brace elevation

Fig. 6: Leg-pile connection joint, full-penetration weld of deck on top of piles

Fig. 7: Full-penetration weld of piles on base-plates, no weld between pile and leg

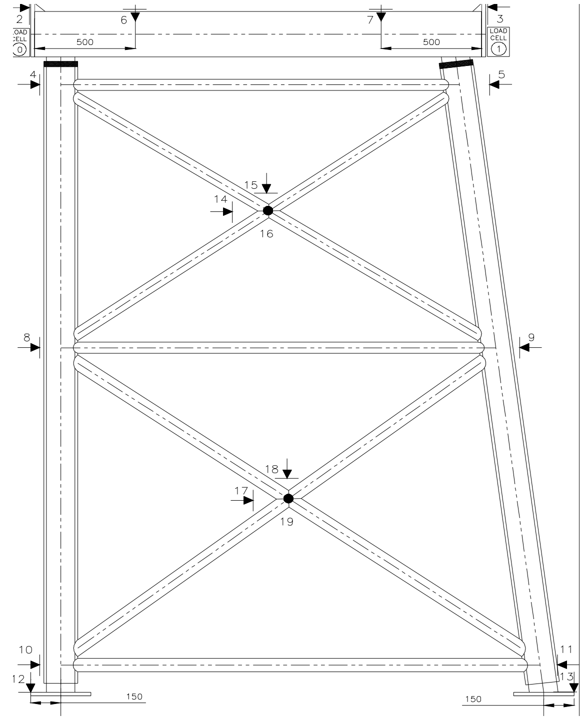

Fig. 8: Load cells and LVDT's arrangement

until making sure the grout is over-flowing out and pre-calculated required volume of grout is completely injected. During the injection, the leg was continuously vibrated in order to avoid air entrapment between pile and leg.

Test setup: The lateral load applied to the frame was measured using load-cells attached to the loading jacks. All joints displacements especially lateral displacement of the frame at all elevations were measured using linear variable differential transformers (LVDT's). The arrangement of load-cells, LVDT's and elasto plastic strain gages (YE-FLA-5 type) are shown in Fig. 8 and 10. Figure 10 presents the details of lateral out of plane constraint supports. These constraints are used to simulate the lateral effect of perpendicular horizontal braces at the elevation of horizontal plans, on the behavior of legs and their free out of plane buckling length.

The prescribed displacement history for the frame models is shown in Fig. 11 and Table 2.

Cycles 8, 9, 14, 21, 28 are five working load cycles at a specified displacement of +/-2Cm. Such cycles have to be included at various points in the history to check the degradation of structural stiffness at working level loads. They are also useful in evaluating numerical models[15].

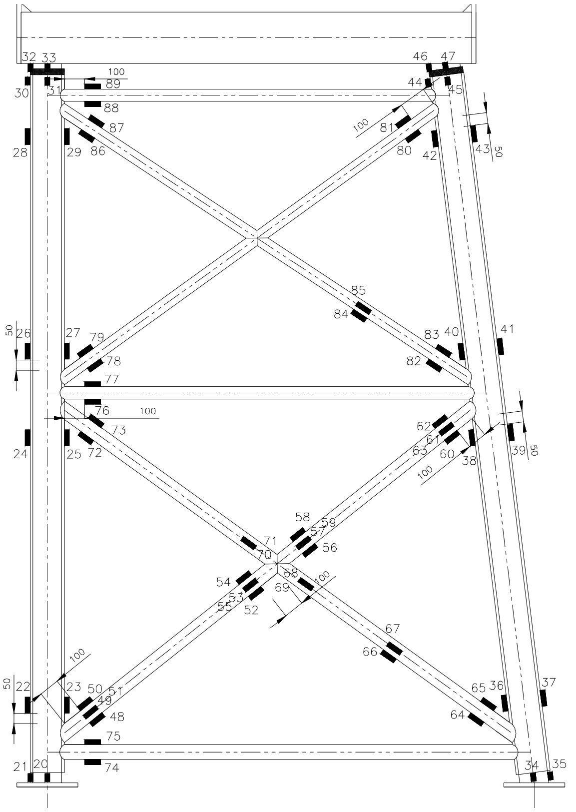

Fig. 9: Strain gages arrangement

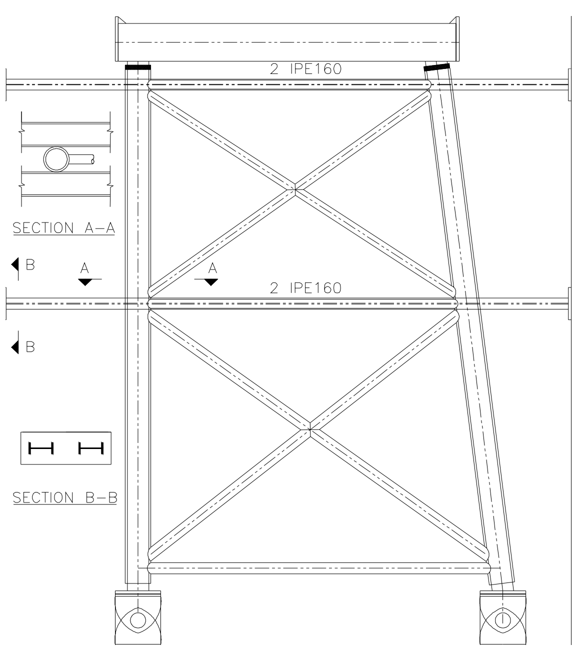

Fig. 10: Out of plane constraint detail at horizontal braces elevation

Table 2: Prescribed Displacement-Controlled Deck Load History

Cycle	Stage	Delta (Cm)	Cycle	Stage	Delta (Cm)	Cycle	Stage	Delta (Cm)
1	1	0.0	11	41	0.0	21	81	0.0
1	2	0.2	11	42	3.0	21	82	2.0
1	3	0.0	11	43	0.0	21	83	0.0
1	4	-0.2	11	44	-3.0	21	84	-2.0
2	5	0.0	12	45	0.0	22	85	0.0
2	6	0.5	12	46	3.5	22	86	9.0
2	7	0.0	12	47	0.0	22	87	0.0
2	8	-0.5	12	48	-3.5	22	88	-9.0
3	9	0.0	13	49	0.0	23	89	0.0
3	10	0.8	13	50	4.0	23	90	10.0
3	11	0.0	13	51	0.0	23	91	0.0
3	12	-0.8	13	52	-4.0	23	92	-10.0
4	13	0.0	14	53	0.0	24	93	0.0
4	14	1.0	14	54	2.0	24	94	11.0
4	15	0.0	14	55	0.0	24	95	0.0
4	16	-1.0	14	56	-2.0	24	96	-11.0
5	17	0.0	15	57	0.0	25	97	0.0
5	18	1.0	15	58	4.5	25	98	12.0
5	19	0.0	15	59	0.0	25	99	0.0
5	20	-1.0	15	60	-4.5	25	100	-12.0
6	21	0.0	16	61	0.0	26	101	0.0
6	22	1.2	16	62	5.0	26	102	14.0
6	23	0.0	16	63	0.0	26	103	0.0
6	24	-1.2	16	64	-5.0	26	104	-14.0
7	25	0.0	17	65	0.0	27	105	0.0
7	26	1.5	17	66	5.5	27	106	16.0
7	27	0.0	17	67	0.0	27	107	0.0
7	28	-1.5	17	68	-5.5	27	108	-16.0
8	29	0.0	18	69	0.0	28	109	0.0
8	30	2.0	18	70	6.0	28	110	2.0
8	31	0.0	18	71	0.0	28	111	0.0
8	32	-2.0	18	72	-6.0	28	112	-2.0
9	33	0.0	19	73	0.0	29	113	0.0
9	34	2.0	19	74	7.0	29	114	18.0
9	35	0.0	19	75	0.0	29	115	0.0
9	36	-2.0	19	76	-7.0	29	116	-18.0
10	37	0.0	20	77	0.0	30	117	0.0
10	38	2.5	20	78	8.0	30	118	21.0
10	39	0.0	20	79	0.0	30	119	0.0
10	40	-2.5	20	80	-8.0	30	120	-21.0

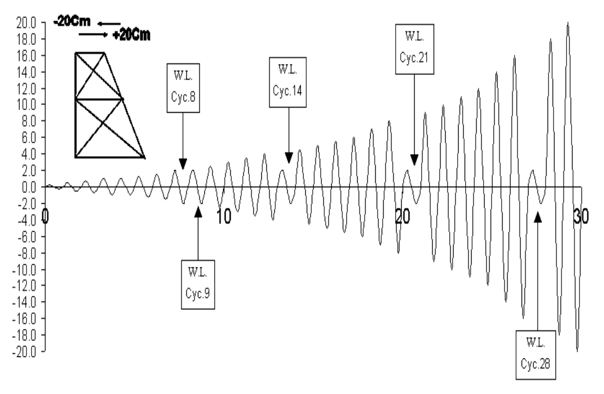

Fig. 11: Prescribed Displacement-Controlled Deck Load History

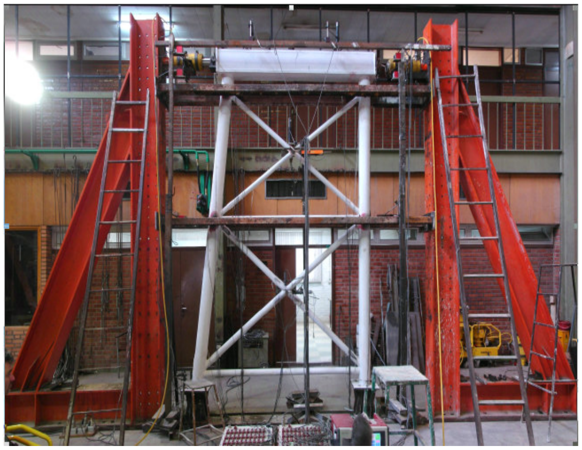

Fig. 12: General view of experimental setup

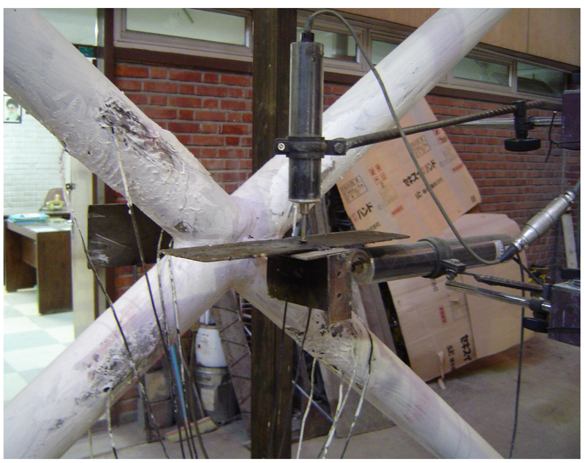

Fig. 13: LVDTs No. 17-19, strain gages 52-59, 68-71

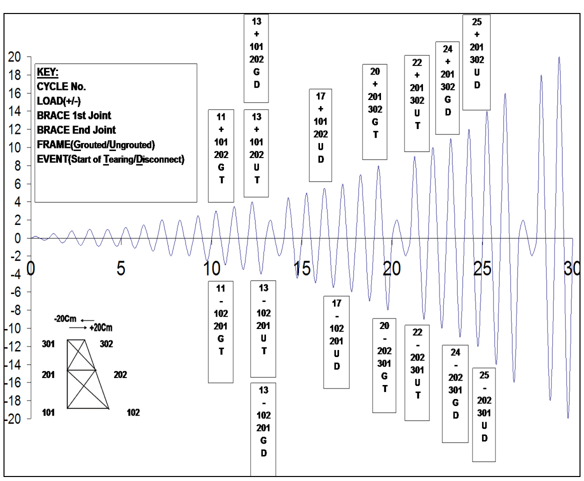

Fig. 14: Summary of events

Fig. 15: Disconnection of x braces in later cycles

Figure 12 and 13 show the experimental setup including the pin support, hydraulic jacks, jacks support frames, lateral constraints, LVDT's, strain gages and general test layout.

RESULTS

Both grouted and ungrouted frames were tested as detailed in previous section exactly in the same conditions. Summary of events and failure mechanism that happened during the tests are shown in Fig. 14. In the absence of joint cans in X braces, tearing failure occurred in the joints of lower and upper panels of both frames. In this test, as explained before, the behavior of braces (which was investigated many times before) were not focused on, but the portal behavior and the effect of grout on overall behavior was to be highlighted, therefore joint cans were not fabricated and a brittle failure has occurred, however the stress-strain curve of the can was derived (by fabricating similar separate X connections) and reported for further numerical efforts. Figure 15 and 16 presents photos showing the failure mechanism that happened during both the tests. In Fig. 16, a picture of the deformed shape of frames in the last cycle is shown.

Overall behavior of test frames: The variation of deck load vs. total deck displacement is presented in Table 3, 4 and Fig. 17-20 for different range of cycles as the hysteretic curves of overall frames behavior compared between grouted case and un-grouted.

There seems not to be a significant difference in hysteretic behaviors of the two cases, but generally it was seen that in grouted case, lateral stiffness of portal elements (only while working in combination with the braces and not as a lone individual lateral system) and

Table 3: Frame load vs. deck displacement (cy 1-30) (un-grouted frame)

Cycle	D(mm)	P(KN)	Cycle	D(mm)	P(KN)	Cycle	D(mm)	P(KN)	Cycle	D(mm)	P(KN)	Cycle	D(mm)	P(KN)	Cycle	D(mm)	P(KN)
1	0.0	0.0	7	-5.9	-15.7	12	-0.5	-4.3	17	34.2	57.2	22	33.0	8.0	26	110.0	25.7
1	0.0	3.1	7	-8.4	-34.9	12	-4.9	-20.0	17	41.0	52.1	22	13.2	-5.4	26	87.0	16.2
1	0.5	4.1	7	-6.0	-6.4	12	-9.4	-56.4	17	31.7	27.2	22	-7.9	-27.5	26	39.3	0.0
1	0.7	3.1	7	-0.5	-0.2	12	-15.3	-106.0	17	17.9	5.4	22	-31.1	-48.7	26	12.2	-8.8
1	0.8	1.3	8	4.5	5.9	12	-19.7	-131.7	17	6.6	-2.9	22	-42.5	-56.0	26	-13.4	-17.8
1	0.6	0.0	8	7.2	21.6	12	-19.5	-117.1	17	-12.7	-22.8	22	-54.5	-65.9	26	-37.1	-26.0
1	0.2	-2.5	8	10.9	51.3	12	-15.2	-65.2	17	-29.9	-52.8	22	-65.3	-74.1	26	-66.1	-34.3
1	-0.4	-4.1	8	13.0	67.0	12	-7.7	-11.5	17	-33.1	-41.6	22	-57.7	-53.2	26	-84.5	-36.7
1	-1.0	-3.3	8	10.5	29.5	12	0.4	4.1	17	-23.2	-20.3	22	-41.7	-30.0	26	-100.0	-37.8
1	-0.7	-1.1	8	5.4	1.8	13	9.7	39.0	17	-5.9	-0.5	22	-15.3	0.0	26	-113.0	-38.3
2	0.1	2.9	8	0.4	-4.3	13	15.0	82.9	18	2.1	4.1	23	4.4	15.1	26	-105.1	-33.6
2	1.0	4.6	8	-3.7	-4.8	13	19.6	121.7	18	15.6	18.3	23	30.7	40.3	26	-82.7	-23.2
2	3.3	4.9	8	-6.0	-17.4	13	25.9	158.3	18	30.9	36.9	23	54.4	56.5	26	-18.5	0.0
2	3.2	2.6	8	-9.4	-46.0	13	22.3	88.1	18	42.4	55.9	23	75.5	62.6	27	16.3	10.5
2	0.6	0.0	8	-9.2	-28.0	13	13.8	20.8	18	43.5	45.7	23	80.5	61.4	27	68.9	24.2
2	0.0	-2.8	8	-5.3	-2.0	13	5.3	-0.2	18	30.6	24.7	23	69.1	40.5	27	118.2	33.1
2	-1.9	-4.3	8	0.6	3.4	13	-3.6	-23.6	18	8.6	0.2	23	49.2	14.1	27	140.3	34.2
2	-3.3	-3.6	9	5.5	9.3	13	-9.2	-67.5	18	-10.6	-19.2	23	30.5	-2.5	27	104.8	19.5
2	-2.7	-1.3	9	9.4	36.2	13	-15.5	-112.2	18	-27.2	-39.2	23	7.0	-20.3	27	50.6	0.0
3	0.1	2.9	9	13.0	67.7	13	-23.0	-145.8	18	-43.6	-60.0	23	-14.7	-36.9	27	25.8	-9.2
3	1.2	4.4	9	11.2	34.7	13	-20.0	-94.0	18	-46.8	-55.9	23	-33.3	-48.8	27	-15.5	-22.0
3	4.0	5.1	9	6.5	4.8	13	-12.6	-33.3	18	-35.3	-35.6	23	-48.0	-56.8	27	-55.1	-32.1
3	5.2	8.0	9	0.4	-4.1	13	-1.7	0.2	18	-17.5	-9.3	23	-59.1	-63.5	27	-89.1	-36.6
3	3.8	2.5	9	-4.7	-6.9	14	1.9	4.3	18	-2.3	3.9	23	-68.6	-66.7	27	-112.2	-37.9
3	0.4	-2.1	9	-7.3	-28.2	14	6.2	20.5	19	18.3	31.0	23	-72.4	-60.2	27	-124.1	-38.7
3	-1.7	-4.3	9	-10.9	-58.2	14	10.6	52.1	19	33.6	51.0	23	-63.9	-48.2	27	-129.2	-37.6
3	-4.2	-4.8	9	-5.9	-5.9	14	11.8	44.4	19	50.3	61.1	23	-47.4	-26.7	27	-104.0	-27.0
3	-5.3	-6.7	9	-0.2	0.2	14	7.1	8.2	19	50.8	50.8	23	-21.8	-0.2	27	-30.1	0.0
3	-4.6	-1.3	10	7.3	20.3	14	0.1	-2.1	19	37.0	28.3	24	16.0	29.0	27	-7.3	5.7
4	0.2	3.6	10	11.0	48.2	14	-3.2	-3.6	19	22.0	6.9	24	43.5	43.4	28	14.9	12.8
4	1.5	4.4	10	14.3	78.8	14	-7.2	-19.8	19	5.0	-3.6	24	58.2	41.3	28	14.7	11.6
4	3.7	4.8	10	15.5	70.3	14	-9.6	-31.1	19	-20.1	-30.6	24	79.2	37.4	28	-3.4	3.9
4	6.6	20.0	10	9.7	19.2	14	-6.6	-5.6	19	-34.1	-47.3	24	93.9	39.3	28	-20.9	-1.1
4	6.1	8.2	10	1.5	0.2	15	0.3	3.4	19	-49.4	-65.6	24	79.2	22.9	28	-20.7	-0.2
4	4.0	2.3	10	1.2	-3.3	15	9.6	39.2	19	-44.3	-49.1	24	61.3	10.2	29	21.0	14.4
4	0.5	-2.3	10	-4.4	-7.4	15	15.5	86.8	19	-20.8	-13.6	24	42.0	0.0	29	77.9	26.5
4	-2.2	-4.3	10	-6.7	-24.9	15	20.0	117.1	20	3.2	6.2	24	20.0	-7.4	29	127.6	34.9
4	-5.0	-9.0	10	-10.2	-55.9	15	24.8	137.6	20	26.1	33.7	24	-6.7	-21.1	29	162.1	37.8
4	-6.0	-7.4	10	-12.7	-77.3	15	28.8	127.8	20	48.1	56.8	24	-28.3	-31.8	29	142.8	28.8
4	-5.1	-1.3	10	-14.2	-76.5	15	29.1	88.0	20	62.2	67.2	24	-50.2	-24.7	29	95.3	10.0
5	0.2	3.1	10	-11.3	-40.3	15	19.8	20.6	20	53.9	46.0	24	-67.2	-32.1	29	62.8	-1.8
5	2.3	4.6	10	-6.2	-6.1	15	16.1	4.1	20	37.6	21.8	24	-80.8	-35.2	29	29.5	-12.9
5	5.4	12.0	10	0.9	4.3	15	4.6	-10.2	20	17.2	0.0	24	-86.2	-35.8	29	-44.5	-30.9
5	6.5	12.1	11	8.4	26.2	15	-6.4	-63.4	20	6.7	-6.7	24	-77.7	-28.9	29	-97.9	-37.9
5	0.7	-0.2	11	12.2	58.5	15	-11.6	-89.1	20	-20.1	-34.9	24	-64.3	-20.3	29	-130.6	-38.8
5	-3.2	-4.8	11	16.2	94.9	15	-19.8	-130.7	20	-37.4	-52.8	24	-12.4	0.0	29	-143.0	-39.0
5	-6.1	-15.9	11	19.6	120.2	15	-28.6	-66.2	20	-49.2	-64.1	25	6.0	5.7	29	-146.4	-36.6
5	-5.6	-3.3	11	16.0	59.5	15	-25.8	-37.8	20	-56.5	-63.1	25	41.4	18.5	29	-107.5	-20.9
6	0.3	3.8	11	10.6	19.7	15	-18.5	-9.8	20	-43.4	-41.0	25	79.8	27.5	29	-43.4	2.2
6	4.7	7.4	11	2.2	0.2	15	-10.3	0.0	20	-24.2	-12.1	25	104.0	30.3	30	24.8	19.5
6	7.9	28.7	11	-3.1	-4.6	16	3.1	19.7	20	-6.7	3.3	25	90.2	24.7	30	96.8	31.6
6	6.4	8.0	11	-7.3	-33.4	16	15.4	48.8	21	5.1	11.1	25	65.7	14.3	30	161.1	37.8
6	0.9	0.2	11	-13.9	-91.1	16	29.3	55.2	21	15.1	24.9	25	26.1	0.2	30	178.6	39.3
6	-1.2	-4.6	11	-16.4	-92.7	16	37.5	66.7	21	12.6	16.4	25	-11.2	-12.0	30	196.6	39.2
6	-4.6	-6.2	11	-15.3	-76.5	16	29.3	22.9	21	3.1	3.8	25	-42.9	-24.0	30	177.1	29.2
6	-6.4	-19.2	11	-7.3	-12.8	16	10.4	-0.2	21	-5.9	-0.8	25	-78.9	-32.4	30	125.2	9.2
6	-6.3	-8.5	11	-0.4	0.0	16	2.0	-4.6	21	-9.8	-3.3	25	-95.4	-33.1	30	24.6	-20.2
6	-0.6	0.0	12	4.5	4.8	16	-9.3	-21.3	21	-12.6	-3.4	25	-84.2	-29.1	30	-25.8	-30.7
7	1.3	4.9	12	9.7	37.2	16	-22.3	-44.0	21	-6.7	-0.2	25	-66.2	-22.4	30	-70.4	-36.7
7	7.2	23.9	12	16.0	90.6	16	-33.1	-58.9	21	-1.8	4.1	25	-44.1	-12.9	30	-130.0	-39.2
7	8.6	34.4	12	22.8	144.2	16	-29.5	-38.0	22	22.3	30.5	25	-11.1	0.0	30	-156.5	-39.2
7	9.5	30.6	12	21.3	106.8	16	-21.8	-19.2	22	43.4	51.8	26	11.0	6.6	30	-178.3	-38.8
7	5.0	1.6	12	15.5	45.9	16	-5.5	-0.2	22	62.4	64.9	26	51.5	19.5	30	-165.7	-31.0
7	0.7	-2.9	12	3.3	0.2	17	4.9	7.7	22	66.7	57.0	26	104.5	31.8	30	-131.1	-18.1
7	-3.5	-4.8	12	2.8	-1.3	17	20.8	36.4	22	49.9	31.3	26	125.6	32.6	30	-85.1	-5.9

Table 4: Frame load vs. deck displacement (cy 1-30) (grouted frame)

Cycle	D(mm)	P(KN)	Cycle	D(mm)	P(KN)	Cycle	D(mm)	P(KN)	Cycle	D(mm)	P(KN)	Cycle	D(mm)	P(KN)	Cycle	D(mm)	P(KN)
1	0.0	0.0	7	-5.9	-20.8	12	12.8	-0.2	18	20.5	26.4	22	-52.9	-32.9	27	12.2	12.0
1	1.8	5.7	7	-8.0	-44.1	12	-1.2	-24.1	18	29.5	39.8	22	-72.2	-38.9	27	65.7	25.9
1	1.8	1.5	7	-9.0	-40.6	12	-13.3	-73.6	18	40.8	55.4	22	-67.7	-26.0	27	122.8	35.7
1	0.5	-1.3	7	-5.9	-6.9	12	-21.8	-40.3	18	43.7	52.4	22	-44.3	-12.6	27	135.4	32.8
1	-0.4	-4.8	7	-0.3	2.0	12	-26.2	-31.9	18	29.3	26.5	22	-8.0	1.3	27	105.5	19.3
1	-1.5	-5.4	8	4.7	7.2	12	-10.3	-5.1	18	7.0	0.2	23	14.5	7.7	27	53.3	0.0
1	-0.8	0.0	8	8.0	34.1	13	8.1	7.5	18	-2.5	-7.4	23	52.1	21.3	27	-8.2	-19.6
2	0.0	4.3	8	10.2	58.7	13	23.0	30.8	18	-19.5	-32.3	23	77.3	27.5	27	-61.2	-33.4
2	2.5	5.1	8	12.3	81.9	13	31.2	40.1	18	-25.9	-41.1	23	81.6	26.4	27	-111.6	-38.6
2	4.2	9.0	8	13.9	82.9	13	22.3	24.1	18	-37.9	-56.5	23	57.4	15.6	27	-138.3	-38.9
2	4.0	2.0	8	10.4	38.3	13	9.6	4.1	18	-43.0	-56.8	23	17.3	0.2	27	-122.0	-31.0
2	0.3	-2.3	8	6.8	6.9	13	-1.0	-3.1	18	-32.6	-37.4	23	-1.2	-5.7	27	-85.8	-17.0
2	-1.6	-4.9	8	0.1	-2.6	13	-16.9	-23.6	18	-17.5	-11.8	23	-12.3	-9.8	27	-38.7	0.0
2	-3.4	-9.5	8	-3.5	-7.5	13	-27.8	-41.3	18	-3.7	1.0	23	-39.2	-19.7	27	-17.2	5.1
2	-3.5	-2.5	8	-6.2	-26.2	13	-21.8	-26.4	19	15.1	20.3	23	-63.3	-28.0	28	6.7	12.5
3	0.2	4.8	8	-9.5	-63.9	13	-9.7	-5.9	19	39.2	52.6	23	-81.6	-36.2	28	17.4	14.9
3	2.6	5.2	8	-11.9	-76.0	14	6.8	4.6	19	55.5	69.1	23	-76.4	-26.7	28	6.8	9.7
3	4.7	11.5	8	-8.7	-29.3	14	13.1	14.1	19	47.9	50.0	23	-59.5	-19.2	28	-21.2	0.3
3	6.1	16.9	8	-1.4	-0.2	14	16.4	16.2	19	32.4	24.1	23	-13.7	0.0	28	-21.8	-0.2
3	5.8	7.7	9	4.9	7.7	14	10.3	6.2	19	11.8	0.2	24	16.9	9.5	29	0.0	8.4
3	0.6	0.0	9	9.7	49.5	14	0.3	-0.8	19	8.5	-3.1	24	69.8	26.0	29	47.3	22.9
3	-0.8	-4.3	9	13.0	88.8	14	-6.2	-5.2	19	-12.4	-27.5	24	95.5	29.2	29	103.7	32.6
3	-3.1	-7.0	9	14.0	86.3	14	-13.1	-15.7	19	-31.7	-50.8	24	72.3	18.5	29	148.0	37.2
3	-5.0	-16.4	9	9.7	31.0	14	-12.9	-11.3	19	-43.5	-65.9	24	24.3	0.2	29	156.1	34.2
3	-5.0	-6.7	9	0.9	0.2	14	-1.1	0.2	19	-51.3	-57.3	24	5.2	-5.2	29	115.6	17.4
3	-1.0	0.0	9	-2.6	-4.9	15	15.6	17.2	19	-41.8	-38.8	24	-22.1	-14.6	29	68.1	0.0
4	7.4	26.7	9	-6.0	-22.4	15	30.8	41.9	19	-27.2	-14.3	24	-51.7	-24.4	29	25.7	-13.2
4	6.5	12.1	9	-10.1	-68.3	15	35.6	49.0	19	-7.9	3.8	24	-77.2	-33.0	29	-19.7	-25.9
4	0.3	-0.2	9	-11.9	-77.3	15	29.0	33.6	20	22.0	35.6	24	-90.3	-36.1	29	-81.2	-36.9
4	-1.7	-4.3	9	-7.4	-15.6	15	21.0	19.8	20	51.7	54.1	24	-84.8	-31.8	29	-122.6	-39.2
4	-4.4	-12.1	9	-1.3	0.0	15	3.3	0.2	20	66.1	51.3	24	-62.8	-19.5	29	-135.3	-38.8
4	-6.1	-25.1	10	8.3	34.1	15	-4.4	-5.4	20	56.2	32.4	24	-15.9	0.0	29	-157.1	-38.8
4	-5.2	-4.9	10	12.5	81.4	15	-17.7	-25.4	20	51.1	24.2	25	17.8	5.7	29	-150.2	-33.8
4	-0.5	2.0	10	16.1	134.0	15	-31.7	-50.3	20	38.1	6.1	25	62.8	16.9	29	-133.8	-28.2
5	3.0	4.9	10	16.9	105.7	15	-25.0	-31.0	20	28.1	0.2	25	104.9	23.6	29	-88.4	-11.7
5	5.7	16.1	10	11.3	34.2	15	-10.9	-6.9	20	11.2	-11.3	25	88.0	19.5	29	-9.7	12.3
5	7.4	25.9	10	1.9	0.2	16	0.6	2.5	20	-13.2	-30.5	25	58.2	11.3	30	71.8	27.5
5	5.7	6.1	10	-2.9	-7.4	16	21.3	26.5	20	-41.7	-54.4	25	26.1	0.0	30	121.4	32.9
5	0.1	-2.3	10	-6.9	-38.8	16	35.8	49.1	20	-51.3	-66.1	25	3.1	-6.4	30	164.8	37.2
5	-2.9	-5.4	10	-11.7	-98.0	16	36.8	45.9	20	-59.6	-54.5	25	-33.8	-20.3	30	191.3	37.5
5	-5.2	-16.4	10	-15.0	-114.8	16	25.1	25.1	20	-46.1	-31.5	25	-77.6	-33.6	30	158.3	23.4
5	-6.0	-11.3	10	-11.8	-53.2	16	4.4	0.2	20	-18.5	0.0	25	-99.6	-35.8	30	113.2	5.7
5	-1.1	0.0	10	-7.7	-7.7	16	-11.1	-15.9	21	3.8	4.6	25	-93.0	-33.3	30	48.5	-14.9
6	5.8	15.4	10	-0.1	4.4	16	-29.4	-45.9	21	12.9	8.2	25	-73.3	-26.2	30	-34.1	-32.7
6	7.6	32.9	11	8.3	39.3	16	-39.5	-60.8	21	15.6	6.7	25	-17.1	-2.6	30	-114.5	-38.5
6	8.8	36.0	11	14.6	102.6	16	-31.4	-38.8	21	-2.6	-0.3	26	26.1	13.6	30	-146.3	-39.2
6	5.4	4.1	11	22.7	117.0	16	-13.9	-8.4	21	-4.3	-0.7	26	75.7	28.5	30	-190.2	-37.9
6	0.5	0.0	11	20.6	59.8	16	-1.5	2.0	21	-7.6	-2.3	26	120.1	35.7	30	-190.8	-32.4
6	-2.4	-4.4	11	14.1	6.1	17	21.6	29.0	21	-15.7	-4.1	26	115.3	32.3	30	-155.3	-16.6
6	-5.1	-16.5	11	-2.4	-39.2	17	43.2	58.8	21	-15.7	-2.6	26	77.5	15.1	30	-100.8	0.0
6	-7.3	-35.6	11	-9.2	-82.1	17	35.0	39.0	21	-7.5	-0.2	26	39.4	0.2			
6	-5.4	-5.1	11	-14.0	-116.3	17	13.4	5.4	22	12.4	23.1	26	15.3	-7.7			
7	1.4	4.6	11	-19.0	-113.2	17	5.1	0.2	22	44.7	32.8	26	-18.0	-19.9			
7	5.8	15.1	11	-12.4	-41.1	17	-7.0	-11.5	22	67.8	39.6	26	-49.2	-29.2			
7	8.7	43.4	11	-3.1	-0.2	17	-26.6	-40.5	22	72.7	32.6	26	-95.0	-37.6			
7	10.8	65.5	12	4.2	9.0	17	-39.9	-60.0	22	60.4	17.2	26	-104.8	-38.0			
7	9.4	34.9	12	14.3	69.8	17	-33.9	-43.6	22	28.9	0.2	26	-116.9	-36.9			
7	6.3	8.8	12	23.0	79.0	17	-20.2	-19.7	22	21.7	-2.9	26	-104.4	-30.2			
7	0.1	-2.3	12	26.8	77.5	17	-3.5	-0.2	22	4.7	-9.8	26	-85.7	-22.0			
7	-3.5	-7.0	12	20.3	12.3	18	5.0	4.8	22	-23.8	-26.0	26	-30.8	0.0			

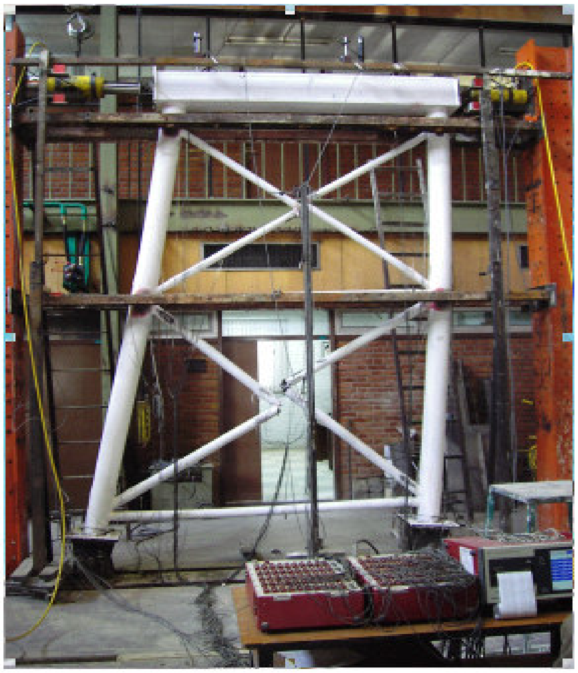

Fig. 16: Platform typical deformed shape (cy. 30, Δ = -20cm), braces all disconnected

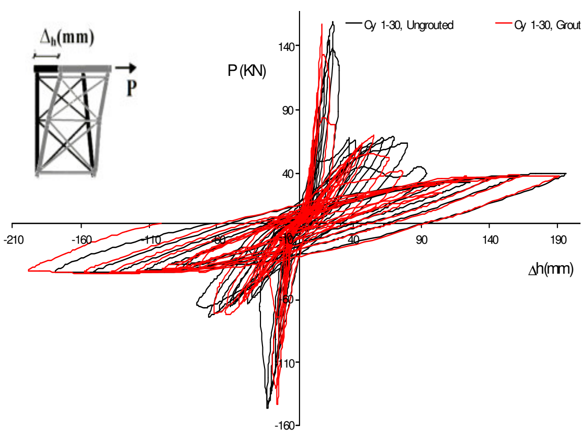

Fig. 17: Frame load vs. deck displacement (cy 1-30)

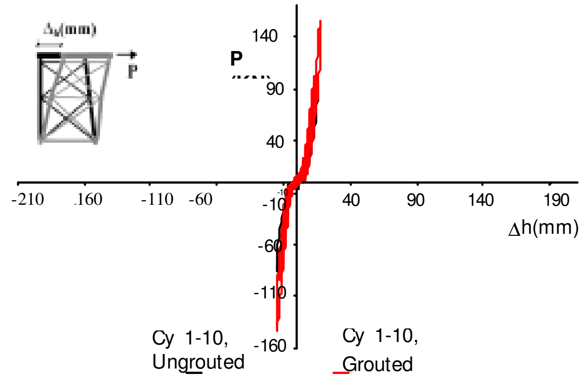

Fig. 18: Frame load vs. deck displacement (cy 1-10)

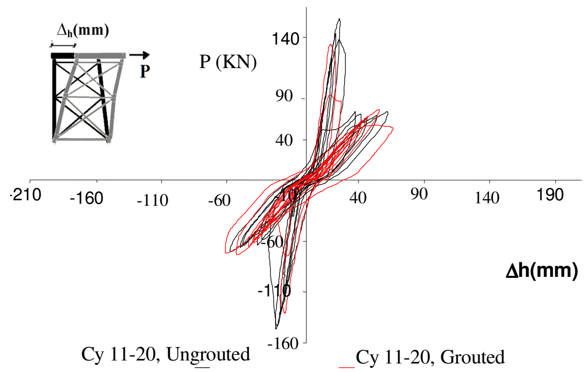

Fig. 19: Frame load vs. deck displacement (cy 11-20)

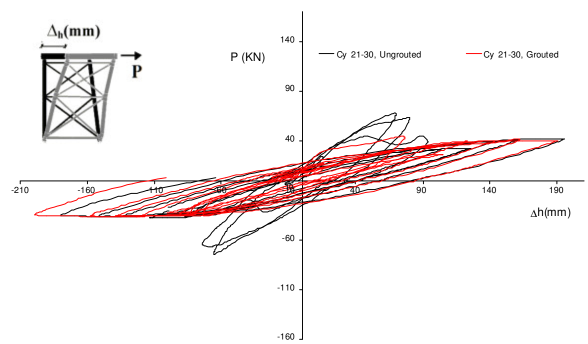

Fig. 20: Frame Load vs. Deck Displacement (Cy 21-30)

therefore lateral stiffness of the grouted frame was more than the un-grouted case. This fact can be seen more clearly in next section where presenting the results for braces. Therefore generally in grouted case, in both stages of failure (in lower and upper panel braces), the braces failed in earlier cycles with lower deck displacements because of the higher rate in increasing the stress in braces.

The lateral stiffness of portal elements while not working in combination with the braces and behaving as the lone individual lateral system (pure portal behavior), is quite the same in both the cases. This fact can be seen in last cycles of hysteretic behavior curves where all X bracings are cut and frame behaves as a pure portal system. This is due to the low effect of grout in the composite section while the section works in bending specially with low values of axial compression[10]. However, while portal elements work in a combined resistant system, grouting can laterally increase the system stiffness due to the effect of braces which can change the bending moment to a couple of tension and compression in two legs and cause the grout to be able to increase the overall frame stiffness. Therefore, regarding the lateral load bearing behavior, two roles and types of behavior for portals can be seen on which the effect of grout is quite different:

- One role is the axial behavior that happens when the braces are working and changing the overturning moment to a couple of tension and compression in the portals. In this case, the whole frame is acting as a combined brace-portal system and grouting can increase the lateral stiffness of the frame because of its important effect on the axial stiffness and strength of compressive portal element. This positive effect of grout is only important when the stiffness of brace system is high and has not gradually been failed or decreased. It means that by degradation of bracing system stiffness, gradually this mentioned effect of grout also decreases. Furthermore in very high ranges of lateral movements, gradually grout would not work because of the development of cracks and its failure in compression
- The other role is when portals behave only in bending as some individual portal elements. In this case grouting does not have any considerable effect on the bending resistance of the portals unless a constant high value of axial force is imposed on them. This fact could clearly be seen in a recent research using post-buckling fiber element[10]. The lateral stiffness of portal elements while not working in combination with the braces is quite the same in both cases. The hysteretic behavior curves of a simple portal element in a jacket-type offshore structure for the grouted or un-grouted cases, do not depict considerable differences for an equal low level of axial load and a good consistency can be seen. The positive role of the grout in lateral stiffness of a single portal element, appears only when it is completely under pressure which happens in high values of constant axial force

The maximum lateral loads per cycles are plotted in Fig. 21. The envelopes of hysteretic curves for both cases are compared in Fig. 22. The energy dissipation per cycle and cumulative dissipation curve are plotted in Fig. 23 and 24. It was found that cumulative energy dissipation curve of grouted specimen is above the un-grouted specimen, but only before tearing happens. Therefore if joint cans had been modeled, tearing would

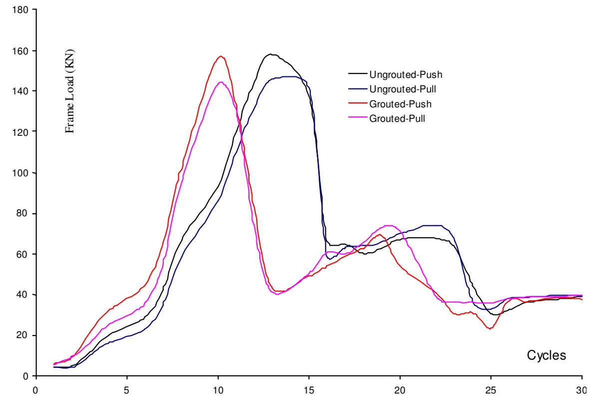

Fig. 21: Frame maximum loads at cycle displacements

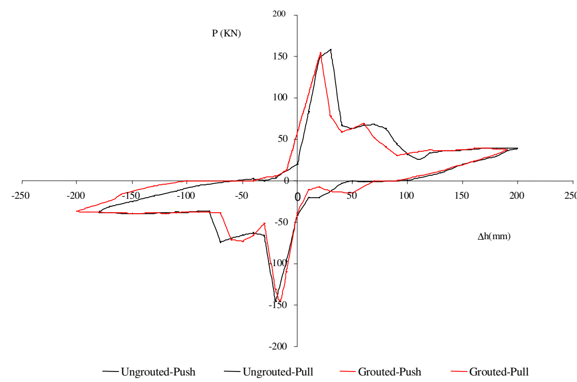

Fig. 22: Frame load vs. deck displacement response envelopes

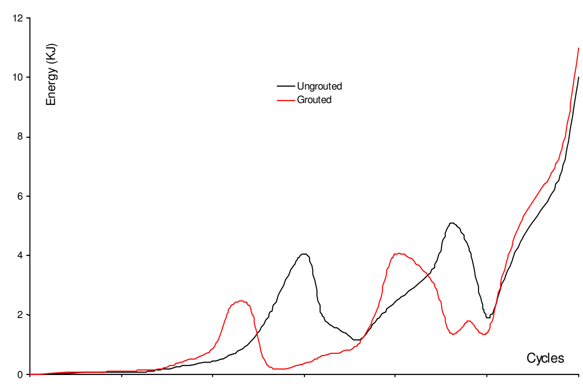

Fig. 23: Frame energy dissipation per cycle

not have happened and the cumulative energy dissipation curve of grouted specimen would have stayed above the one for un-grouted.

The degradation of structural stiffness at working level loads can be seen and compared in Fig. 25 for

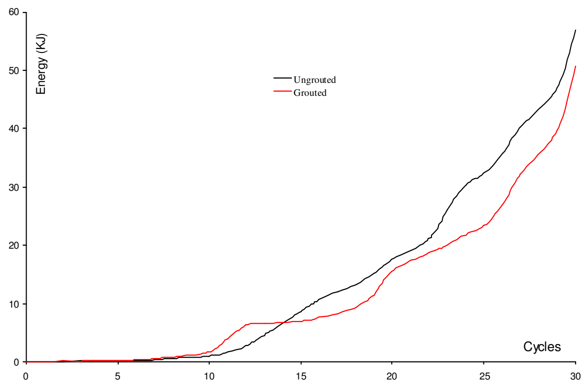

Fig. 24: Frame cumulative energy dissipation

both cases. No significant difference in behavior degradation sequence can be seen between two cases.

Behavior of members: It was described in previous section that generally in grouted case, lateral stiffness of portal elements (while working in combination with the braces) and therefore lateral stiffness of the grouted frame were more than un-grouted and when the stiffness of one system (portal system increases, the applied load on the 2nd system with constant stiffness also increases while a unique similar displacement is applied to whole the combined systems. This higher rate in increasing the stress in braces can be seen more clearly in Fig. 26-29 where the results of test are presented for individual braces.

It should be noted that strains recorded by strain gages were changed to pipes stresses, using measured stress-strain relation curve. Furthermore, the axial stresses and bending stresses could be seen separately, by having the strain in different points of sections.

DISCUSSION

In this study, a new series of experimental data were produced, using a modified scaled model much more similar to real condition in aspects of pile-leg interaction and can be used in evaluating numerical models.

There was not a significant difference in hysteretic behaviors of the two cases. It was seen that in grouted case, lateral stiffness of portal elements (while working in combination with braces) and therefore lateral stiffness of the whole frame were higher than in the un-grouted case. Regarding the lateral load bearing behavior, two different roles and types of behavior for portals were distinguished and the effect of grout on each was investigated.

When the stiffness of portal system, while working in combination with the braces, increases, the applied load on the bracing with constant stiffness also increases while a unique similar displacement is applied to the combined systems as a whole. In this condition, axial stresses in braces of grouted frame increase more rapidly than in un-grouted case and cause the increase in lateral stiffness of the frame. Therefore in grouted case, the braces failed in earlier cycles with lower deck displacements and approximate same maximum lateral loads. Also cumulative energy dissipation curve of grouted specimen is above the un-grouted one but only before tearing happens in braces. However if joint cans had been considered, tearing would not have happened, braces would have shown plastic behavior and the cumulative energy dissipation curve of grouted specimen would have stayed above the un-grouted one before any tearing happens. Grouting generally will increase the stiffness and energy absorption of the frame, provided that the joint cans be modeled and the braces be able to demonstrate post-buckling behavior.

Five working load cycles were included at various points in the history to check the degradation of structural stiffness at working level loads. No significant difference in behavior degradation sequence can be seen between the two cases.

ACKNOWLEDGEMENT

The research employed herein was sponsored under POGC (Pars Oil and Gas Company) project No. 65 “Nonlinear Dynamic Behavior of Offshore Platforms”. The financial support of POGC is gratefully acknowledged.

The tests were performed by BHRC (Building and Habitation Research Center) of Habitation Ministry of Islamic republic of Iran, in structure laboratory. BHRC is gratefully acknowledged.

REFERENCES

1. Amoco Production Co, 1983. Lateral Stability of Piles in Ungrouted Jacket Legs, (USA), OTC004645.
2. API, 1993. Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms, Working Stress Design, API (RP2A-WSD).
3. Asgarian, Aghakouchack, 2004. Nonlinear Dynamic Analysis of Jacket Type Offshore Structures Subjected to Earthquake Using Fiber Elements, 13th World Conference on Earthquake Engineering, Vancour, B.C., Canada, August 2004, Paper No.1726.

4. Asgarian, Aghakouchak and Bea, 2005. Inelastic Post-Buckling and Cyclic Behavior of Tubular Braces, J. Offshore Mechanics and Arctic Eng., Vol. 127.
5. Asgarian, Aghakouchak and Bea, 2006. Nonlinear Analysis of Jacket-Type Offshore Platforms Using Fiber Elements, J. Offshore Mechanics and Arctic Eng., Vol. 128.
6. Bea, R.G., 1992. Seismic design and requalification methodologies for offshore structures. California Inst. of Tech., Pasadena, CA.
7. Bea, R.G., 1993. Seismic response of offshore platforms. X-National Conference on Earthquake Engineering, Ja1isco, Mexico.
8. Ghanaat, Y. and R.W. Clough, 1980. Shaking Table Tests of a Tubular Steel Frame Model, Report No. UCB/EERC-82/02, Earthquake Engineering Research Center, University of California, Berkeley.
9. Higginbortham, A.B., 1973. The Inelastic Cyclic Behavior of Axially-Loaded Steel Members, Disseration, University of Michigan, Ann Arbor, January 1973.
10. Honarvar, Bahaari and Asgarian, 2007. Effect of Grouting in Jacket Type Offshore Platforms Pile-Leg Interaction in Nonlinear Range of Deformation, J. Offshore Mechanics and Arctic Eng., OMAE-07-1007, (Accepted for publication).
11. Kayvani, K. and F. Barzegar, 1993. Modeling of Tubular Members in Offshore Steel Jacket Under Severe Cyclic Loading, Report No. R-324, the University of New South Wales, Australia.
12. Wimpey Laboratories Ltd., 1982, The Reappraisal of Steel Jacket Structures Allowing for the Composite Action of Grouted Piles, OTC004194.
13. Wimpey Offshore Engineers and Constructors Ltd., 1987. New Test Data on the Capacity of Cement-Filled Steel Tubulars, OTC005484.
14. Zayas, V.A., E.P. Popov and S.A. Mahin, 1980. Cyclic inelastic buckling of tubular steel Braces. Report No. UCB/EERC-80/16, University of California, Berkeley, CA.
15. Zayas, V.A., S.A. Mahin and E.P. Popov, 1980. Cyclic inelastic behavior of steel offshore structures, Report No. UCB/EERC-80/27, University of California, Berkeley, CA.
16. Zayas, V.A., S.A. Mahin and E.P. Popov, 1981. Inelastic Structural Analysis of braced p1atforms for seismic loading. Proc. 0ffshore Tech. Conf., American Iron and Steel Inst., 259-272.
17. Zayas, V.A., P.B. Shing, S.A. Mahin and E.P. Popov, 1981b. Inelastic structural modeling of braced offshore p1atforms for seismic loading. Report No. UCB/EERC-81/04, University of California, Berkeley, CA.