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A Verification Study of ASCE Recommended Guidelines for Seismic Evaluation and Design of Combination Structures in Petrochemical Facilities

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Abstract: This study focuses on how the interaction between piping and the supporting pipe-ways can affect the seismic behavior of the whole system. For this purpose, the considered pipe-way structures have been assumed to support multiple pipes so that the weight of the piping can be either about 25% of the pipe-way structure, or in some cases more and some cases less than that amount to evaluate how the ASCE code recommendation for analyzing the combination structures, such as piping and pipe-way, separately or as a whole system is valid. The effects of various combinations of different dimensions pipes, pipes end-conditions and stiffness of connecting links of on pipe-way piping on the system responses have been also discussed. Analytical results show that not only the weight percentage of piping, but also the stiffness of connection links and the dimensions of supported pipes and their end-conditions are also important factors affecting the whole system behavior and may cause the system conditions to be different from the code assumptions.

Key words: Piping, pipe-way, seismic assessment, U-bolt links, time-history analysis, primary-secondary system

INTRODUCTION

Many kinds of piping, made of various materials and having different dimensions are vastly used in petrochemical facilities for transferring fuel oil or high pressure gases from some equipment or a specific production site to another one. Most of the containing materials in such pipes are actually hazardous materials that if released they would have in-site and off-site destructive consequences. Regarding the fact that few industrial sites have been affected by the past earthquakes, reports about sustained damages and seismic behavior of industrial equipments and structures are limited. Also, in the walkthrough investigations of industrial plants, damaged due to the past earthquakes, because of damages imposed to heavy and major structures, fires and falling of the adjacent structures on piping, adequate attention has not been paid to such facilities disruptions. As a result, there are just few codes, guidelines or recommendations for seismic design and/or evaluation of non-building structures located in industrial plants. Therefore, in many cases of seismic assessment of combined structures such as on pipe-way piping, which have an important role in maintaining the operation, dynamic interactions between connected structures and/or equipments are neglected. Neglecting the interactions can lead to some variations in estimated response of either pipes or pipe-way and resulting stresses, which can finally lead to under- or over-estimation of design requirements. This in turn can result in unreliable or un-economical seismic design. Obviously, the unreliable design can lead to major damages, as shown in Fig. 1a and b, which would interrupt operation of the whole industrial complex for long time to carry out the repair works. Regarding these facts, developing simplified methods and their inclusion in codes and guidelines are of great importance in civil and mechanical engineering communities for practical applications.

From the research viewpoint, some studies have been conducted for seismic analysis of the combined primary-secondary systems as a single unit and several methods have been developed for simplified analysis of such systems. In simplified methods, analysis of seismic behavior of combined systems are broadly classified into two groups: (1) coupled analysis and (2) decoupled analysis. In the coupled analysis cases, the combined Eigen properties of the primary-secondary system are determined by considering the two sub-systems as a single and independent dynamic unit and modal analysis is carried out for investigating their seismic behavior (Igusa and Der Kiureghian, 1985; Veletsos and Ventura, 1985). Since, the masses and stiffnesses of the secondary system are usually small compared to those of the primary system, there may be ill-conditioning of matrices in the proposed simplified methods (Ray and Gupta, 2002). The real Eigen properties of the classically damped

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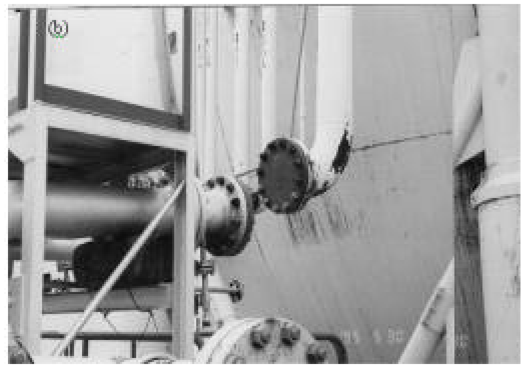


Fig. 1(a, b): Deformation and damages of piping and pipe-ways (Suzuki, 2008)

sub-systems have also been used in the evaluation of the combined systems properties (Igusa *et al*., 1983; Suarez and Singh, 1987). Some studies have been also carried out for decoupling combined systems to sub-systems and formulating the exact transfer functions directly in terms of the fixed-base modes of the individual sub-systems (Dey and Gupta, 1998, 1999; Gupta, 1997; Rao, 1998). Also, several attempts have been made for developing methods for decoupling analysis of the two sub-systems, such as floor response spectrum, frequency-based, response-based and mode-acceleration (Asfura and Der Kiureghian, 1986; Burdisso and Singh, 1987; Reddy *et al*., 1998; Surya *et al*., 2002) and some criteria have been proposed and compared for this purpose (Chen and Wu, 1999). Some studies have been carried out as well on influences of primary and secondary systems, assumed as rigid blocks, on each other's dynamic behavior for which various connection conditions have been considered (Der Kiureghian, 1999; Sharif *et al*., 2009).

In all of the aforementioned studies the primary-secondary system is assumed to be composed of two sub-systems: (1) supporting sub-system, which is mostly the heavier sub-system, as the Primary and (2) supported sub-system, which is mostly the lighter sub-system as the multiply-supported secondary. It should be mentioned that the multiply-supported secondary sub-system has been considered as just a single dynamic system, while in the case of on pipe-way piping systems, especially in industrial complexes, usually there are varieties of pipe combinations with different diameters, connecting links and end conditions, which create several secondary sub-systems instead of just one. Therefore, assumption of a single secondary system for decoupling the equations of motion could lead to gross errors in response predictions of such primary-multiple secondary systems.

One of the guidelines, widely accepted by engineering communities for aseismic design of the petrochemical structures, is the ASCE Guidelines for Seismic Evaluation and Design of Petrochemical Facilities (ASCE, 1997). Other codes and reports also exist for designing and retrofitting of piping systems such as ASME Code for Pressure Piping, B31.3 (ASME, 1999) and its (a) and (b) addenda as well as ALA Report on Seismic Design and Retrofit of Piping Systems (ALA, 2002).

In section 4.4.3 of ASCE document it is stated that if the weight of the nonstructural element is less than about 25% of the weight of the structure, or if the nonstructural element is rigid, interaction effect need not be considered. This study focuses on validation of this ASCE proposed design and evaluation provision and discusses how the interaction between multiple piping and pipe-way with respect to the limitations presented in the ASCE guidelines can affect the seismic behavior of the whole system. By performing several Time History Analysis (THA) it has been investigated that how the piping combination, connecting U-bolt rings and end-conditions could affect the seismic responses of the whole system in comparison with the pipes and pipe-way systems as separate structures. The pipe-way structures have been assumed to support multiple pipes so that the weight of the piping can be either about 25% of the pipe-way structure, or in some cases more and some cases less than that amount to evaluate how this ASCE recommendation for analyzing the piping and pipe-way separately or as a whole system is valid.

For the considered THA four different acceleration time histories at three different PGA levels have been used and the finite element method with beam elements has been employed to assess the earthquake induced forces on the systems. Two different piping combinations have been assumed supported on the pipe-way structures to find out the effects of the pipes dimensions on the system responses. The on pipe-way piping has been assumed to be laterally and vertically restrained with U-bolt supports on frame structures' main beams, which are usually used in industrial plants, while it's longitudinal and rotational movements have been assumed to happen freely.

DESCRIPTION AND MODELING OF THE STUDIED STRUCTURES

For selecting a real case of on pipe-way piping system for this study, some petrochemical facilities were visited in Imam Port Petrochemical Complex, located in South of Iran at the Persian Gulf shore. In the visited facilities there were many types of piping and supporting structures having various lengths, heights, supporting levels and piping dimensions, end conditions and so on. The overall view of one of the actual systems considered for this study and the close up view of the used U-bolt supports of the pipes on main beam of the frame supports are shown in Fig. 2a and b.

Obviously, any combination of the mentioned features could result in some special behavior and analytical conditions. The selected structures for this study are located in Low Density Poly Ethylene (LDPE) producing part of the petrochemical site, which support many types of high pressure piping containing actually toxic and hazardous materials. Details of profile sections of the supporting structures' frames were obtained from the technical drawings of the selected structure, designed and built in late 70s Imam Port Petrochemical Complex (1977). The spacing between the main lateral frames of the pipe-way structures in longitudinal direction is usually 8.0 m and the structures usually have a mid-span gravity deformation controlling beam between each two adjacent frames. The piping in many cases was attached to the pipe-way structures using U-bolt supports at upper wing of the main frame beams as the bolts diameter were equal for all different dimensions piping. Some of these bolts were disconnected at maintenance or repair works from the piping and were not assembled at their location again which could induce much deflection of piping under extreme loads such as earthquakes. In this study, it has been assumed that all U-bolt rings are assembled and their absence has not been modeled in the seismic analysis, since the randomness in this absence is very high and it is very time-consuming to consider all possible cases. In many cases the frames of the pipe-way structure supports piping at two different levels for carrying more pipes. This feature was also considered in the support structures in this study.

The structure for which the results of analysis are presented in this study includes six main lateral frames at

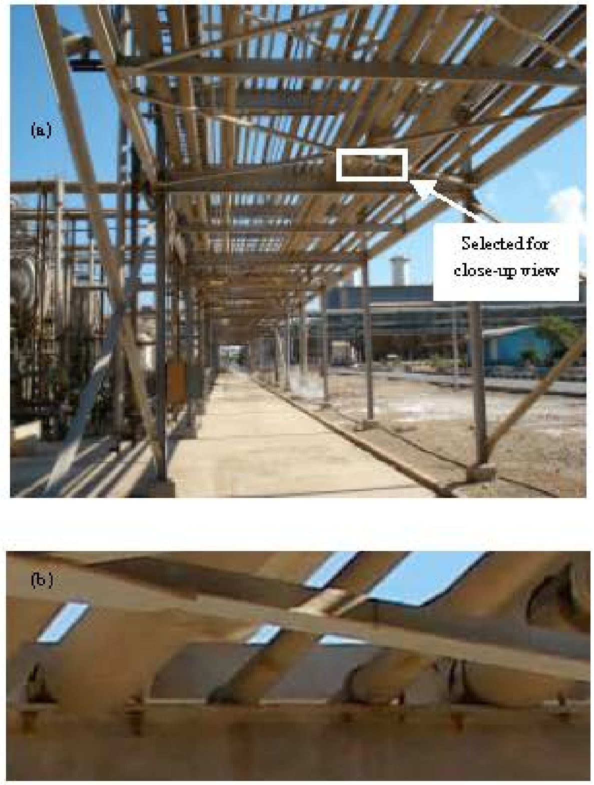


Fig. 2: The overall and close-up views of the sample structure of the study, (a) overall view of the sample selected combination structure and (b) the close-up view of the U-bolt supports of main beams

8.0 m spacing, giving a total length of 48.0 m for the whole pipe-way structure. The actual selected frame structure supports a set of pipes weighing more than 50% of its weight at two levels with 4.4 and 5.6 m heights. Bracing of the pipe-way in actual system is in longitudinal direction and horizontal levels at every other 5 spans and there is no bracing in transverse direction to facilitate the access for repair and maintenance works. These features were considered in the structural models of the sample systems.

To achieve the goals of the study, the combination structures of piping and pipe-way were modeled with different weight ratios of piping to supporting structure of 15, 25 and 35%. The pipes cross-sectional dimensions were considered as 70.0×2.6, 159.0×4.0 and 419.0×6.3 mm. As it was observed in visited sites, just one or two branch line(s) of large diameter pipes were supported on upper level of frame structures. Hence, in this study it was decided to develop the structural models in two main piping combinations, as shown in Table 1.

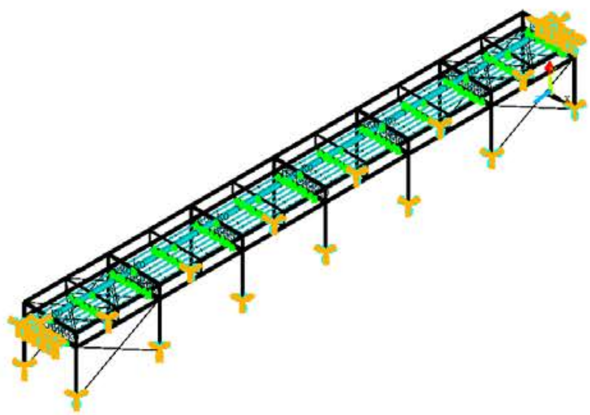


Fig. 3: The overall view of the whole structural model of the sample system

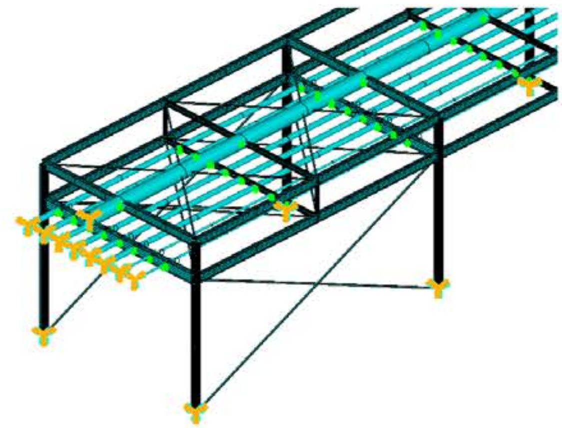


Fig. 4: The close-up view of a part of the structural detailed model

Table 1: Number of pipes of various dimensions in considered pipe combinations for various weight ratios

	Weight ratios (W^P/W^S)					
	15%		25%		35%	
	1st	2nd	1st	2nd	1st	2nd
Pipe dimensions (mm)	(Pipe combination)					
70×2.6	2	2	6	2	6	2
159×4.0	4		6	3	9	6
419×6.3		1		1		1

W^P: Pipe weight, W^S: Structure weight

As it is seen in Table 1 in the first combination for all weight ratios just pipes with diameters of 70.0 and 159.0 mm were used, but in the second combination pipes with diameters of 70.0 and 419.0 mm were used for 15% weight ratio, while pipes with diameters of all three considered values were used to reach the desired weight ratios of 25 and 35%. Also to find out the effects of the stiffness of U-bolt links on the responses of the whole systems, the rods of 4.0, 6.0 and 8.0 mm diameters were used in structural models.

For more detailed investigation of the responses in various conditions, it was assumed that the end conditions of all pipes supported on frame structures would be one of the following cases:

- Both ends are fixed, indicated hereinafter as F-F
- One end is fixed and the other one has a spring type support, indicated hereinafter as F-S
- Both ends have spring type supports, indicated hereinafter as S-S

These spring type supports were applied at all six components of the pipes end nodes to take into account the effect of remaining parts which can not be included in the structural model. The stiffness values of these springs were derived using the assumption that the continuing parts of the pipes have a vertical bend attached to a heavy structure at ground level. The total length of the piping supported by the 48.0 m pipe-way was assumed to be 50.0 m, letting the pipe to pass 1.0 m over with respect to each of the end frames of the pipe-way structure. Figure 3 and 4 show respectively the overall view of the structural model created by the computer program for the 48.0 m long pipe-way structure, supporting pipes of various diameters in two different levels and a close up view of it which shows more detail of the structural model of the system and its connections.

STIFFNESS OF THE U-BOLT CONNECTING RINGS

As it was shown in Fig. 2b, the U-bolt rings encircle the pipes, so that they constrain transversal and vertical movements of pipes, but let them move freely in longitudinal direction to avoid thermal stresses due to expansion or contraction, or similar deformations in piping. For taking into account the lateral stiffness of the U-bolt rings in finite element models of the combined structures, some two-node compression-tension spring elements were assumed to connect the pipes' lower nodes to the main beam upper nodes just beneath them. For obtaining the springs' stiffness values, finite element modeling of the U-bolt rings in presence of the pipes were carried out, to get the realistic behavior of rings in contact with pipes. To find out the effect of rings' stiffness on the responses of combined structures, diameter of bolts were assumed to be 4.0, 6.0 and 8.0 mm in the analyzed models. Regarding that three different diameters were assumed for pipes and also three different diameters for the rings'

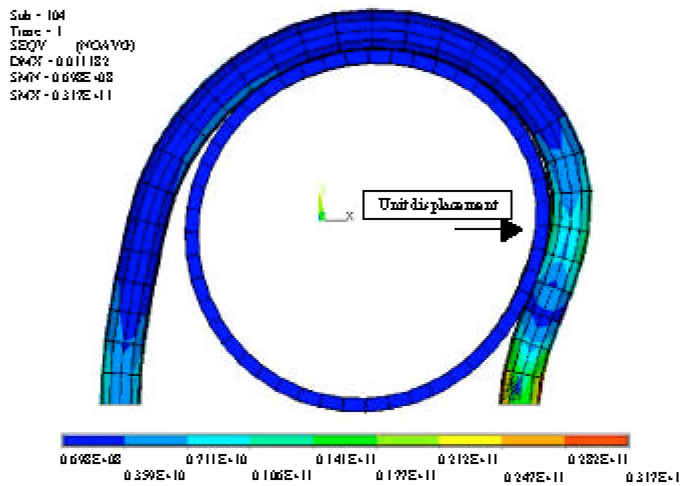


Fig. 5: Final deformed shape of the 70×2.6 mm pipe and 8.0 mm ring rod combination subjected to a lateral unit displacement

Table 2: Calculated lateral stiffness values of U-bolt rings (kN m^{-1})

	Pipe dimensions (mm)		
U-Bolt rod diameter (mm)	70×2.6	159×4.0	419×6.3
4.0	2312.2	344.1	24.0
6.0	5746.6	834.0	82.2
8.0	11937.0	1657.8	141.6

rods, nine sets of finite element contact analysis were needed for obtaining the rings' stiffness. For modeling flexible-to-flexible contact between ring and pipe solid elements, the Penalty Function method with minimum penetration were used. This method was utilized by Hallquist *et al.* (1985) and Nakajima and Padovan (1987) for contact-impact problems. A comprehensive review of the method with particular emphasis on computational aspects has been presented as well (Aliabadi and Brebbia, 1993).

To get a realistic solution of the equations related to described analytical models of pipe and ring the outer elements of pipe wall as well as ring body should be defined as both contact and target elements. Contact condition was set to sticking state, where no gap exists between the two bodies and no sliding takes place. Also for convergence of the calculations friction forces between elements were neglected. Figure 5 shows the final deformed shape of one of analyzed models, composed of pipe with 70.0×2.6 mm dimensions and ring with rod diameter of 8.0 mm subjected to a lateral unit displacement applied at the indicated node of the pipe inner surface.

The deformation of the pipe cross-section and the gap between the outer surface of the pipe and the U-bolt ring can be seen clearly in Fig. 5. The calculated lateral stiffness values of U-bolt rings for various pipe-ring combinations are shown in Table 2.

Values shown in Table 2 have been used for lateral spring connections of pipes' beam elements, employed for seismic analysis of on pipe-way piping.

EARTHQUAKE RECORDS FOR THE THA

The acceleration records of four earthquakes, given in Table 3, scaled to three different PGA levels of 0.3, 0.5 and 0.7 g were used for THA in this study.

Figure 6, which is related to the KJM-000 component of Kobe earthquake as a sample of the used records, shows the acceleration time history and its Fourier amplitude spectrum of the record which indicates its frequency content.

As it can be seen in Fig. 6, the frequencies higher than 1.0 Hz with large Fourier Amplitudes of Kobe acceleration record used in this study, starts from 1.19 Hz with other peaks at 1.45, 1.91, 2.09, 2.29, 2.58 and 2.88 Hz. These values are discussed later in the paper with regard to the dominant frequencies of the on pipe-way piping systems.

DISCUSSION ON NUMERICAL RESULTS OF THE THA

Regarding that various parameters can affect the seismic response of the on pipe-way piping systems and considering the main goal of this study some sets of parameters, including the piping weight ratio, pipes combination in the setting and pipe dimensions, pipes end-conditions and the diameter of the U-bolt rods were considered in THA. The considered results contain displacement response time histories of the system in its various points, including the frame corner, the mid-span

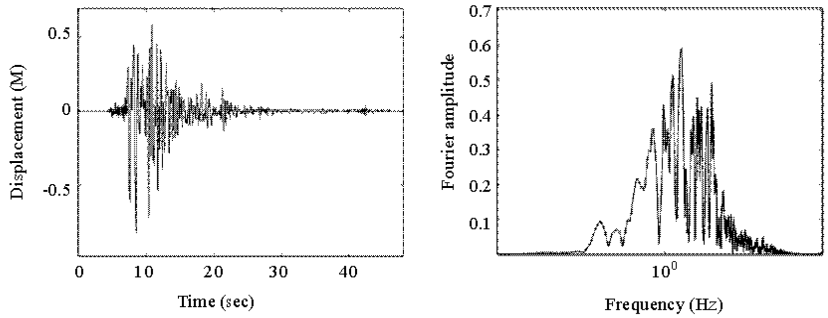


Fig. 6: Acceleration time history of KJM-000 component of Kobe earthquake and its Fourier amplitude spectrum

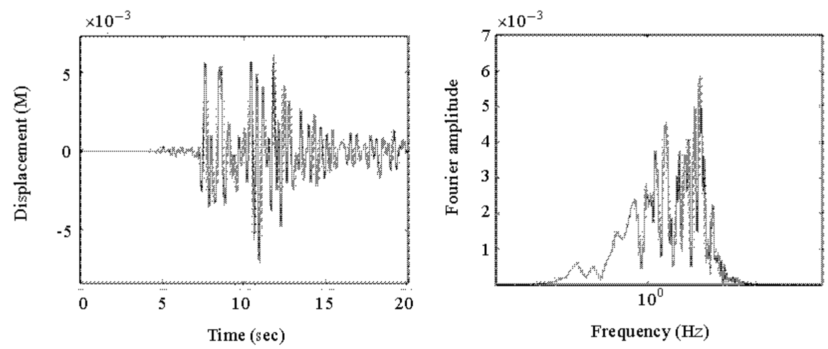


Fig. 7: Time history and Fourier amplitude spectrum of displacement response of the corner point of pipe-way frame, analyzed individually subjected to KJM000 component of Kobe earthquake

Table 3: Specifications of the earthquake records used in the study

Earthquake	Component	PGA (g)	Dominant frequency (Hz)
Kobe	KJM000	0.821	1.453
Kocaeli	DZC270	0.358	0.537
Loma Prieta	CLS000	0.644	1.416
Northridge	SPV360	0.939	4.468

of the pipes as well as the Fourier amplitude spectra and dominant frequencies of those response time histories. Just some samples of results, related to on pipe-way piping system with 48.0 m length of pipe-way and pipes being 50.0 m long and having different weight ratios of 15, 25 and 35% are presented here in Fig. 7-18 and Table 4-10. More result cannot be presented here because of lack of space and can be found in the main report of the study (Azizpour, 2009).

The first set of results relates to the pipe-way frame and the pipes, modeled and analyzed individually subjected to KJM000 component of Kobe earthquake, scaled to 0.3 g. Figure 7 shows the displacement response time history of pipe-way frame corner point and its Fourier amplitude spectrum.

As shown in Fig. 7, the extreme values of displacement response of pipe-way frame, modeled as an individual structure subjected to scaled KJM000 component of Kobe earthquake and the corresponding dominant frequencies are, respectively -6.98E-3 m and 2.88 Hz. This value is same as the highest dominant frequencies of the used earthquake accelerogram. It is worth mentioning that the fundamental modal frequency of the pipe-way structure is 3.51 Hz, which is higher than 2.88 Hz and therefore the structure's frequency has not been able to dominate the seismic response.

Figure 8-10a and b show the same results for mid-span points of the considered pipes of various diameters in two cases of U-bolt rod diameters of 4.0 and 8.0 mm only for F-S end conditions because of lack of space. Results of other cases can be found in the main report of the study (Azizpour, 2009).

Based on Fig. 8-10 the extreme values of displacement responses of pipes with various diameters, connection and end conditions, modeled as individual structures subjected to KJM000 component of Kobe earthquake, scaled to 0.3 g and the corresponding dominant frequencies are as shown in Table 4.

Comparing the extreme values of displacement responses and their corresponding dominant frequencies of the pipe-way frame and pipes of various diameters, modeled individually, shows that these responses are quite different in both amplitude and dominant frequency.

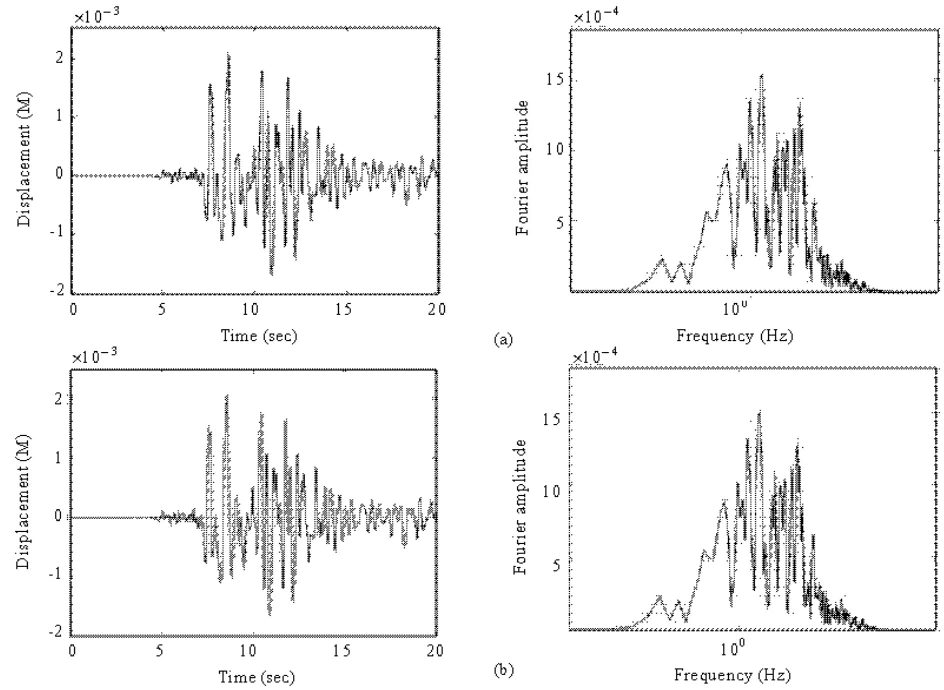


Fig. 8: Time history and Fourier amplitude spectrum of displacement response of mid-span point of the 70*2.6 mm diameter pipe, analyzed individually subjected to KJM000 component of Kobe earthquake. In the case of U-bolt rod with (a) 4.0 mm and (b) 8.0 mm diameter

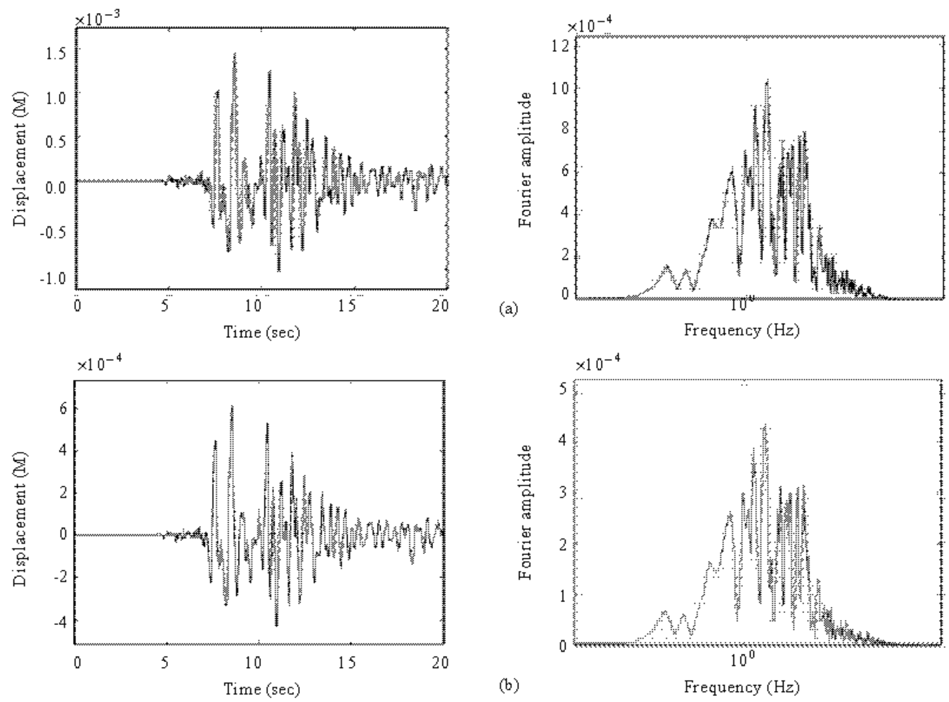


Fig. 9: Time history and Fourier amplitude spectrum of displacement response of mid-span point of the 159*4.0 mm diameter pipe, analyzed individually subjected to KJM000 component of Kobe earthquake. In the case of U-bolt rod with (a) 4.0 mm and (b) 8.0 mm diameter

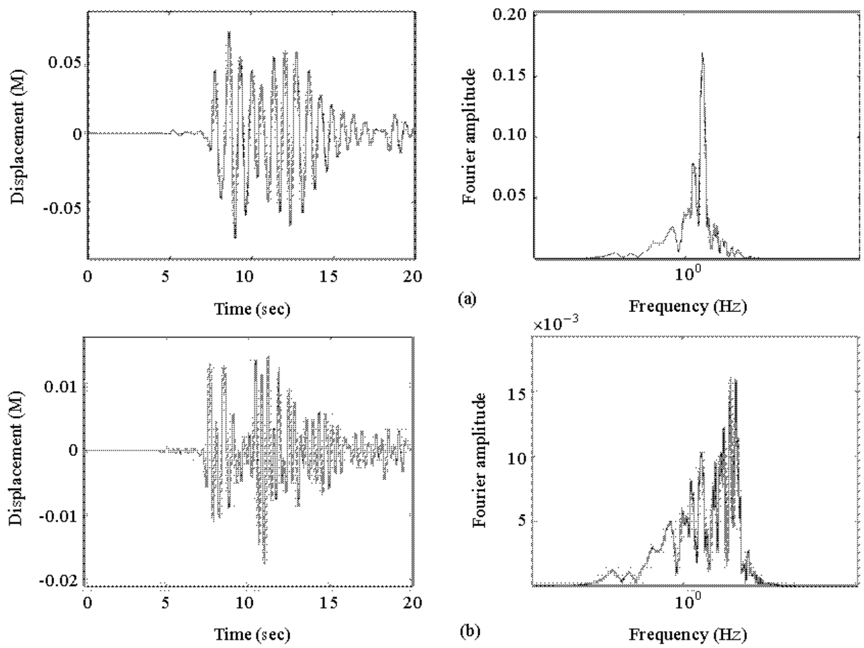


Fig. 10: Time history and Fourier amplitude spectrum of displacement response of mid-span point of the 419×6.3 mm diameter pipe, analyzed individually subjected to KJM000 component of Kobe earthquake. In the case of U-bolt rod with (a) 4.0 mm and (b) 8.0 mm diameter

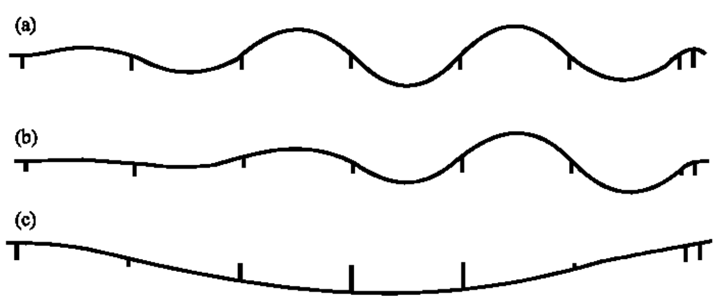


Fig. 11: The fundamental mode shapes of the three considered pipes of the study, modeled as individual structures, for F-S end conditions and U-bolt rod diameter of 4.0 mm. In the case of the (a) 70×2.6, (b) 159×4.0 and (c) 419×6.3 mm pipe

It can be observed that for the 70×2.6 mm pipe the extreme displacement responses have all the same value of about 0.22 cm for all end conditions and both U-bolt rod diameters of 4.0 and 8.0 mm, while for the 159×4.0 mm pipe the extreme displacement responses are almost independent of the pipe end conditions, but are dependent on the U-bolt rod diameter, resulting in a value of around 0.14 cm for 4.0 mm rod and around 0.06 cm for 8.0 mm rod. In the case of 419×6.3 mm pipe both end conditions and U-bolt rod diameter are effective on the extreme response values, which are varying from -1.7 cm for F-S end condition and U-bolt rod diameter of 8.0 mm to 9.8 cm for S-S end conditions and U-bolt rod diameter of 4.0 mm. The reason behind these differences is the relative stiffness of the pipe and its ring restrains as described hereinafter in more details.

Concerning the dominant frequencies, it can be seen in Table 4 that the value of this parameter is 1.465 Hz for both 70×2.6 and 159×4.0 mm pipes irrespective of their end conditions and the U-bolt rod diameter, while for 419×6.3 mm pipes has values varying from 1.416 Hz for F-S and S-S end conditions and 4.0 mm U-bolt rod diameter, to 2.832 Hz for F-F end conditions and 8.0 mm U-bolt rod diameter. To find out if the dominant frequency in each case is related to the input or the structure itself, the fundamental modal frequencies of the three

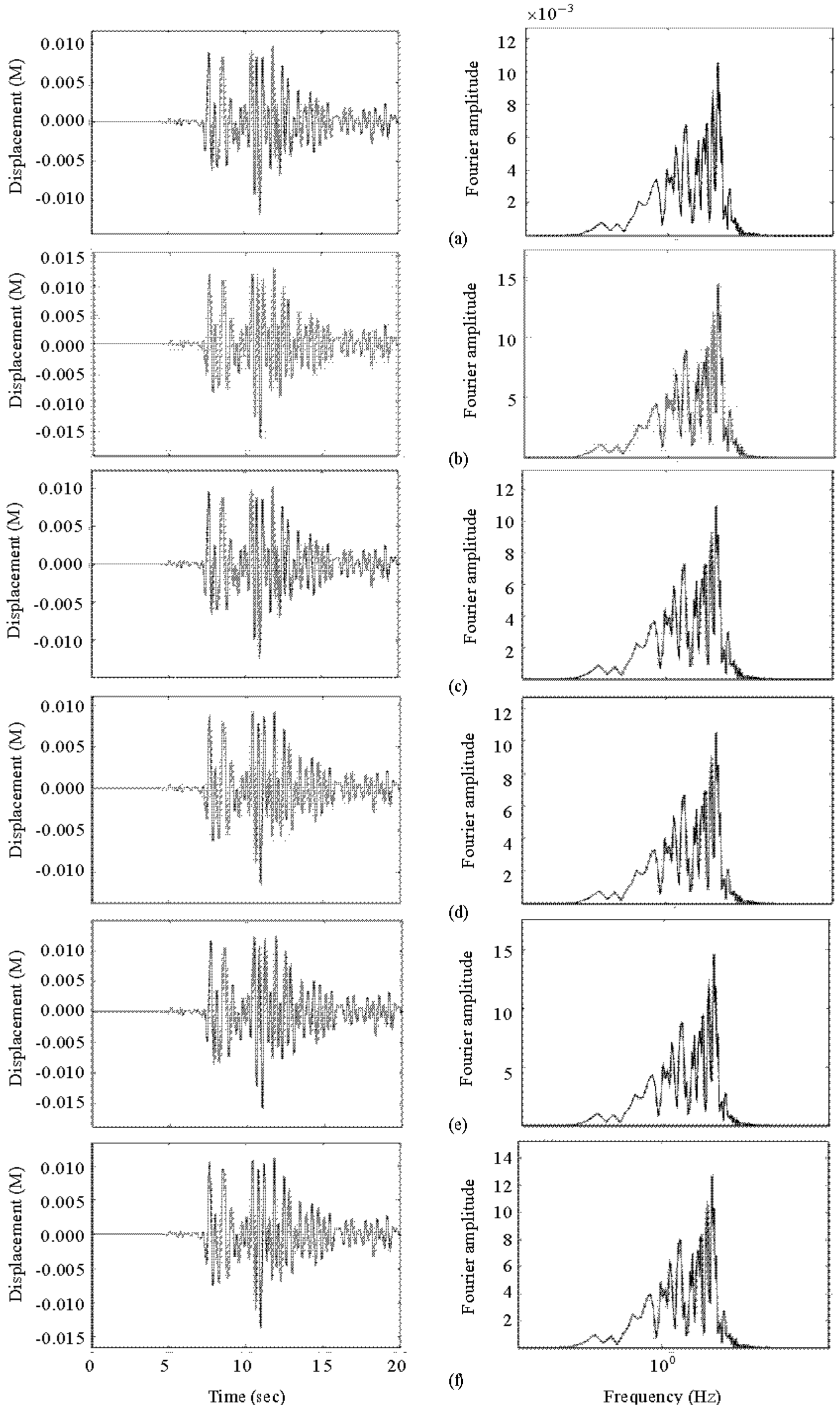


Fig. 12: Time history and Fourier amplitude spectrum of displacement response of on pipe-way piping at its various points in the case of first combination for 15% weight ratio, subjected to KJM000 component of Kobe earthquake, (a) At frame corner in the case of 8.0 mm rod and F-F end conditions, (b) At mid-span of the 70×2.6 mm pipe with 8.0 mm rod and F-F end conditions, (c) At mid-span of the 159×4.0 mm pipe with 8.0 mm rod and F-F end conditions, (d) At frame corner in the case of 4.0 mm rod and S-S end conditions, (e) At mid-span of the 70×2.6 mm pipe with 4.0 mm rod and S-S end conditions and (f) At mid-span of the 159×4.0 mm pipe with 4.0 mm rod and S-S end conditions

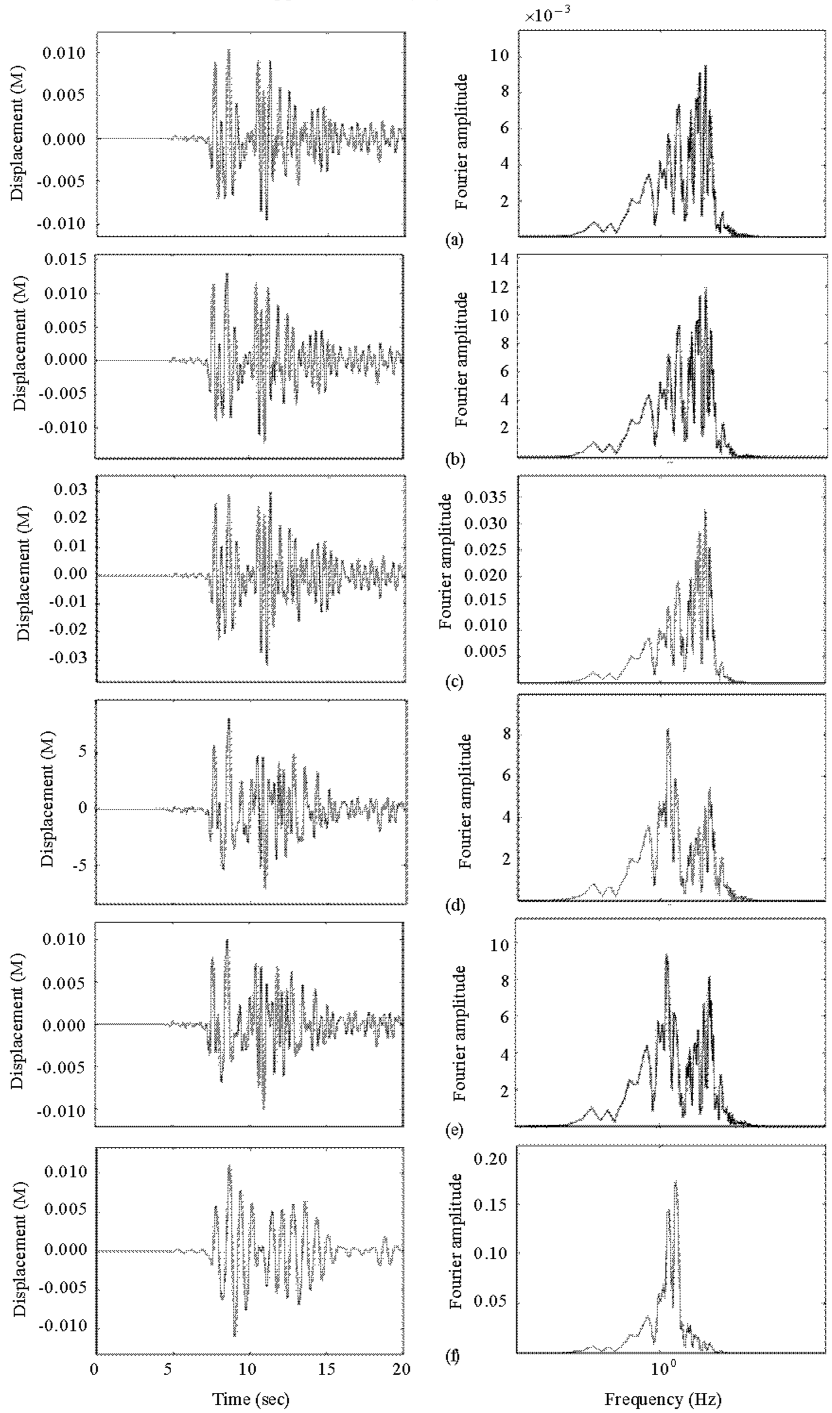


Fig. 13: Time history and Fourier amplitude spectrum of displacement response of on pipe-way piping at its various points in the case of second combination for 15% weight ratio, subjected to KJM000 component of Kobe earthquake, (a) At frame corner in the case of 8.0 mm rod and F-F end conditions, (b) At mid-span of the 70×2.6 mm pipe with 8.0 mm rod and F-F end conditions, (c) At mid-span of the 419×6.3 mm pipe with 8.0 mm rod and F-F end conditions, (d) At frame corner in the case of 4.0 mm rod and S-S end conditions, (e) At mid-span of the 70×2.6 mm pipe with 4.0 mm rod and S-S end conditions and (f) At mid-span of the 419×6.3 mm pipe with 4.0 mm rod and S-S end conditions

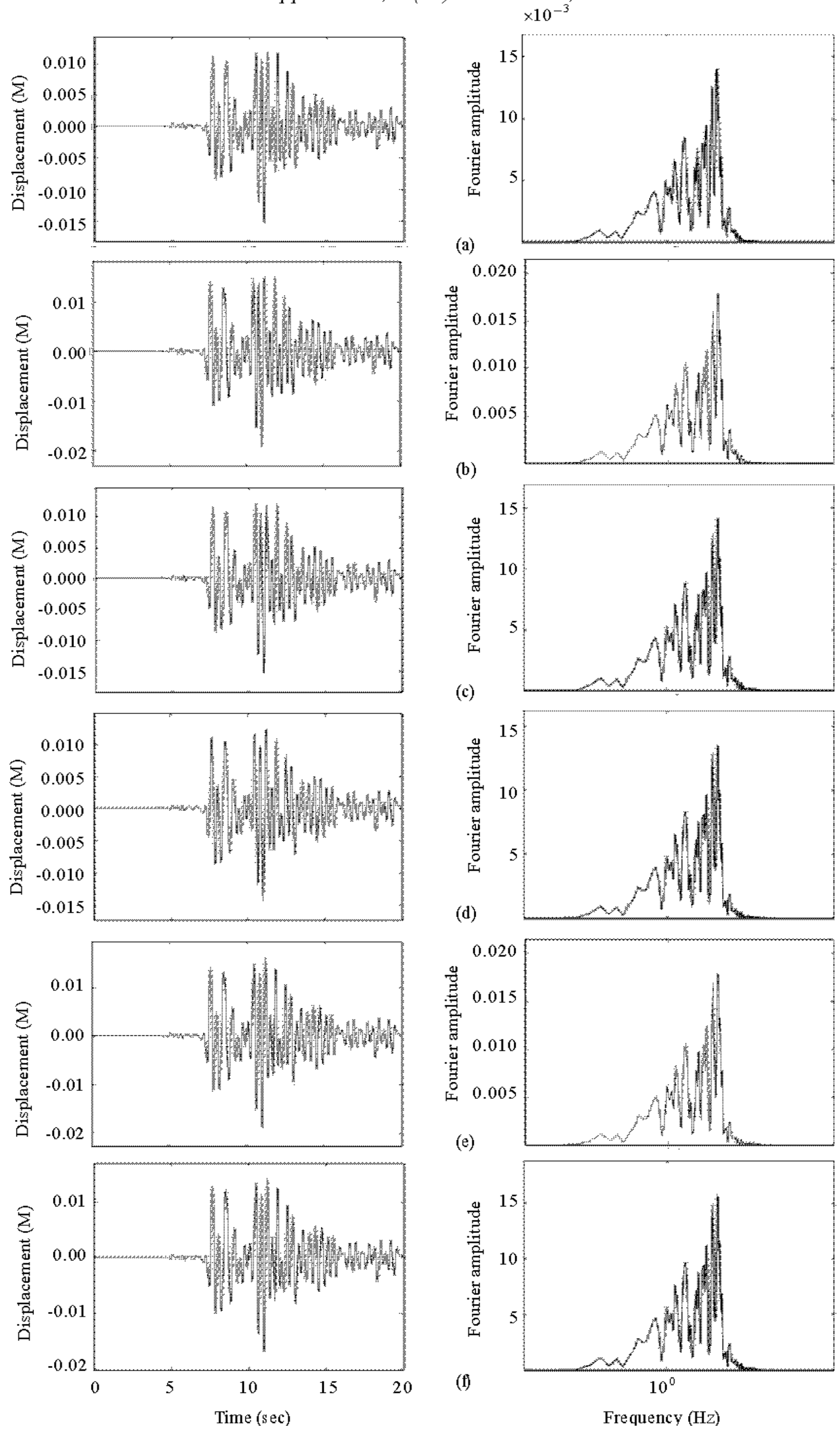
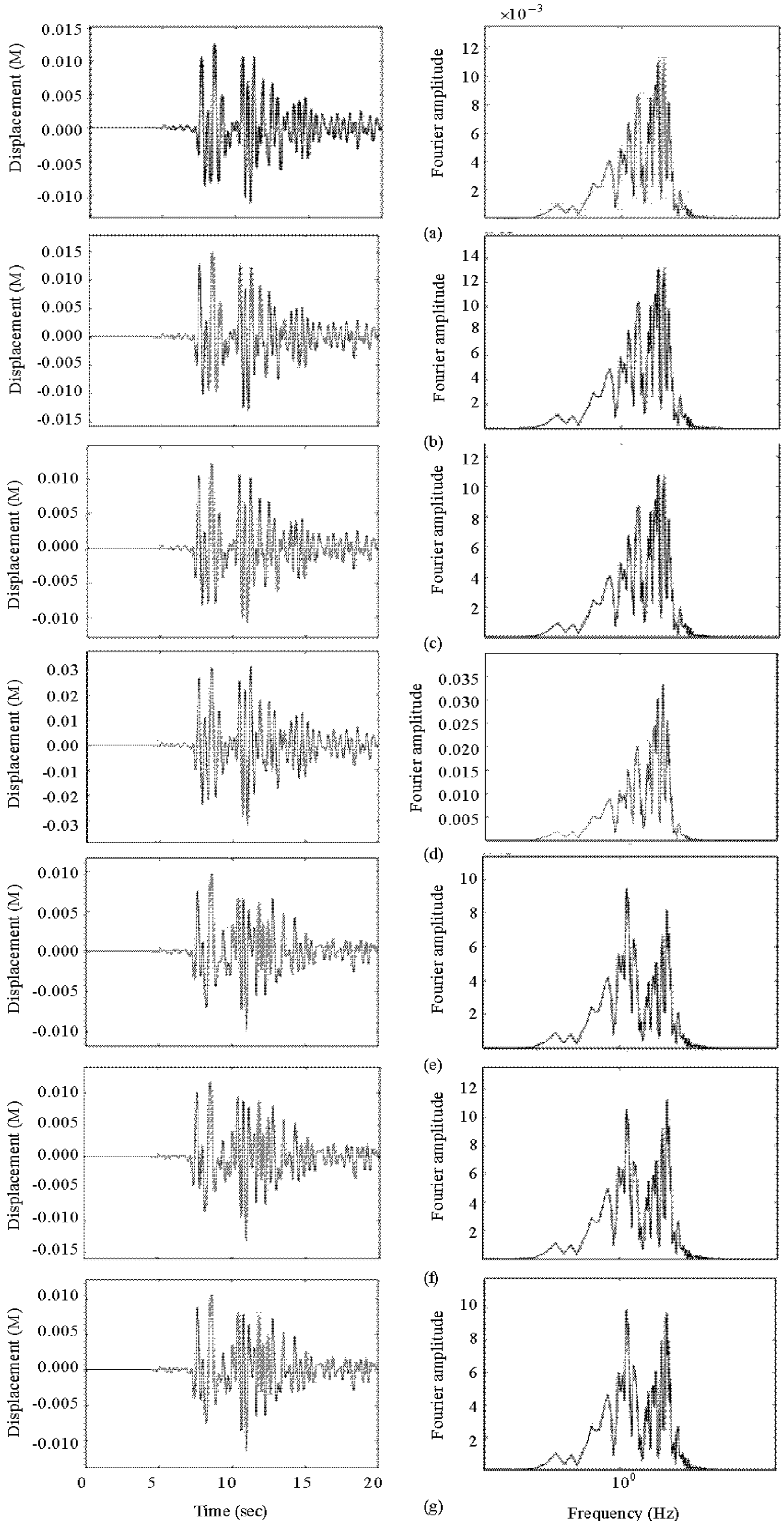


Fig. 14: Time history and Fourier amplitude spectrum of displacement response of on pipe-way piping at its various points in the case of first combination for 25% weight ratio, subjected to KJM000 component of Kobe earthquake, (a) At frame corner in the case of 8.0 mm rod and F-F end conditions, (b) At mid-span of the 70×2.6 mm pipe with 8.0 mm rod and F-F end conditions, (c) At mid-span of the 159×4.0 mm pipe with 8.0 mm rod and F-F end conditions, (d) At frame corner in the case of 4.0 mm rod and S-S end conditions, (e) At mid-span of the 70×2.6 mm pipe with 4.0 mm rod and S-S end conditions and (f) At mid-span of the 159×4.0 mm pipe with 4.0 mm rod and S-S end conditions



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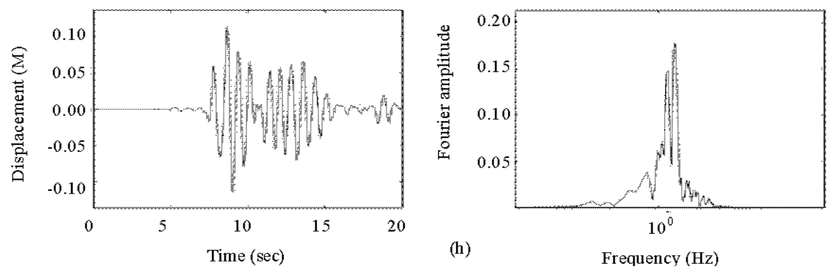

Fig. 15: Time history and Fourier amplitude spectrum of displacement response of on pipe-way piping at its various points in the case of second combination for 25% weight ratio, subjected to KJM000 component of Kobe earthquake, (a) At frame corner in the case of 8.0 mm rod and F-F end conditions, (b) At mid-span of the 70×2.6 mm pipe with 8.0 mm rod and F-F end conditions, (c) At mid-span of the 159×4.0 mm pipe with 8.0 mm rod and F-F end conditions, (d)At mid-span of the 419×6.3 mm pipe with 8.0 mm rod and F-F end conditions, (e) At frame corner in the case of 4.0 mm rod and S-S end conditions, (f) At mid-span of the 70×2.6 mm pipe with 4.0 mm rod and S-S end conditions, (g) At mid-span of the 159×4.0 mm pipe with 4.0 mm rod and S-S end conditions and (h) At mid-span of the 419×6.3 mm pipe with 4.0 mm rod and S-S end conditions

Table 4: Extreme values of displacement responses and the corresponding dominant frequencies of pipes with different conditions, modeled as individual structures subjected to KJM000 component of Kobe earthquake

		Pipes dimensions					
	U-Bolt	70×2.6 mm		159×4.0 mm		419×6.3 mm	
Pipes end conditions	rod diameter (mm)	D_{max} (m)	f_{max} (Hz)	D_{max} (m)	f_{max} (Hz)	D_{max} (m)	f_{max} (Hz)
F-F	8.0	0.002143	1.465	0.000614	1.465	-0.01787	2.832
	4.0	0.002185	1.465	0.001448	1.465	-0.06439	1.465
F-S	8.0	0.002064	1.465	0.000611	1.465	-0.01757	2.588
	4.0	0.002111	1.465	0.001446	1.465	-0.07614	1.416
S-S	8.0	0.002305	1.465	0.000625	1.465	-0.01914	2.588
	4.0	0.002342	1.465	0.001457	1.465	-0.09795	1.416

Table 5: The fundamental modal frequencies of the three pipes (in Hz) in the case of F-S end conditions, modeled as individual structures

	Pipe dimensions (mm)		
U-Bolt rod diameter (mm)	70×2.6	159×4.0	419×6.3
4.0	3.133	6.894	1.414
8.0	3.135	7.126	2.790

pipes in the case of F-S end conditions, modeled as individual structures are shown in Table 5.

It is seen in Table 5 that the fundamental modal frequencies of the 70×2.6 mm pipe in both cases of U-bolt rod diameter have almost the same value of 3.13 Hz, while for the 159×4.0 and the 419×6.3 mm pipes they are different values for different U-bolt rod diameters. The lower fundamental frequencies of the 419×6.3 mm pipe comparing to other two pipes relate to the structural conditions and the relative stiffness of the pipe and the U-bolt rings, which results in different dynamic behavior in this case. In fact, the low stiffness of the 70×2.6 and the 159×4.0 mm pipes relative to the U-bolt rings makes the behavior of the system similar to a multi-span beam, while the high relative stiffness of the 419×6.3 mm pipe relative to the U-bolt rings makes the dynamic behavior of the pipe similar to a very long-span beam with some lateral weak restrains. These different behaviors can be observed in Fig. 11, which shows the fundamental mode shapes of the three considered pipes, modeled as individual structures for F-S end conditions and U-bolt rod diameter of 4.0 mm.

Figure 12-17a-f show the displacement response time histories of the system, subjected to KJM000 component of Kobe earthquake scaled to 0.3 g, in its various points, including the frame corner, the mid-span of the pipes as well as the Fourier amplitude spectra of those response time histories for different combination structures, creating various weight ratios of 15, 25 and 35%.

It can be seen in Fig. 12 and 13 that although the extreme values of displacement responses of the combination structure at its different points are different, the general forms of all time histories are almost the same, except for the case of 4.0 mm U-bolt rod diameter in the second combination, which is due to the high relative stiffness of the 419×6.3 mm pipe to the U-bolt rings, leading to the dominancy of the 419×6.3 mm pipe dynamic characteristics (Fig. 11) in the whole combination system

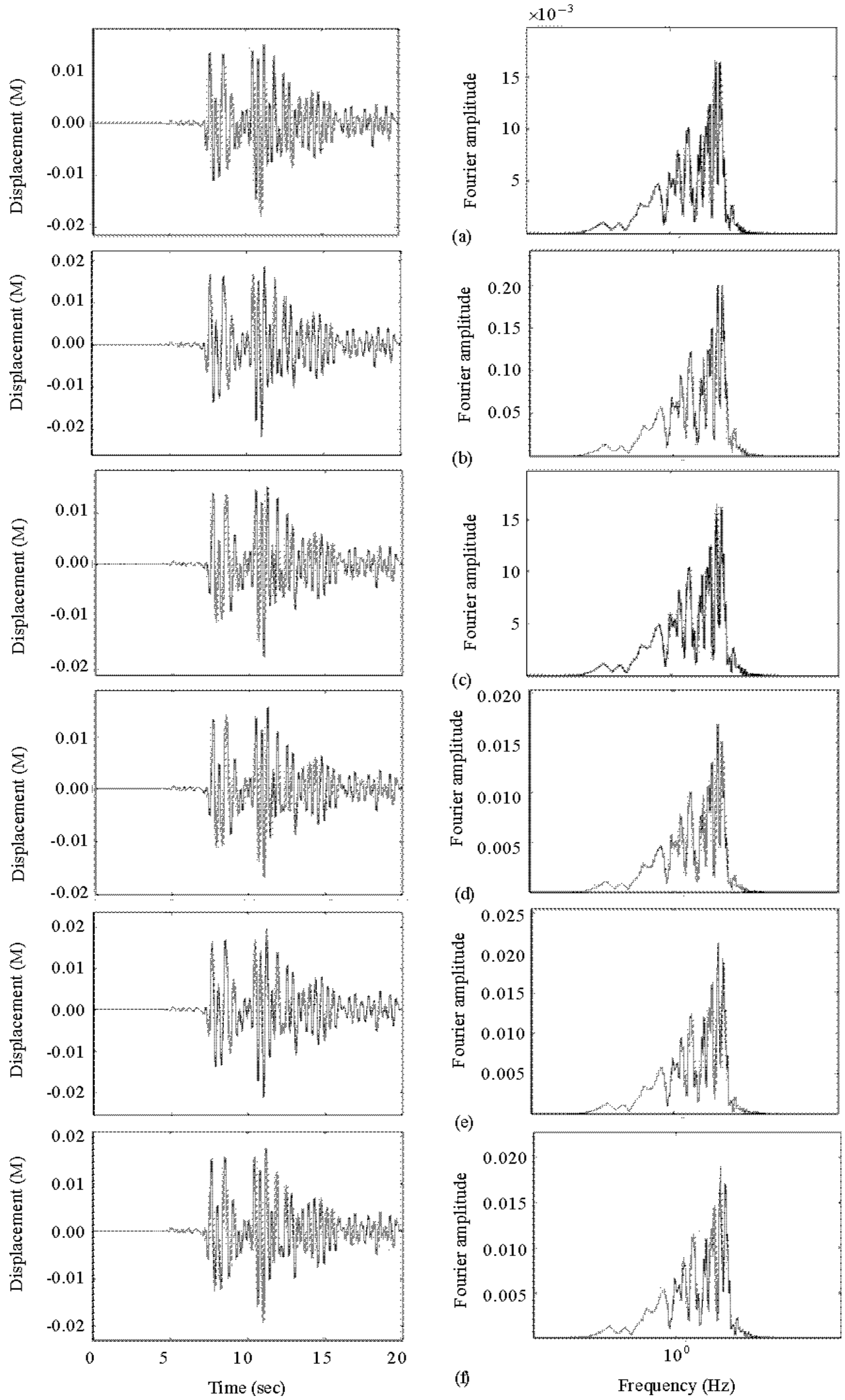

Fig. 16: Time history and Fourier amplitude spectrum of displacement response of on pipe-way piping at its various points in the case of first combination for 35% weight ratio, subjected to KJM000 component of Kobe earthquake, (a) at frame corner in the case of 8.0 mm rod and F-F end conditions, (b) at mid-span of the 70×2.6 mm pipe with 8.0 mm rod and F-F end conditions, (c) at mid-span of the 159×4.0 mm pipe with 8.0 mm rod and F-F end conditions, (d) at frame corner in the case of 4.0 mm rod and S-S end conditions, (e) at mid-span of the 70×2.6 mm pipe with 4.0 mm rod and SS end conditions and (f) at mid-span of the 159×4.0 mm pipe with 4.0 mm rod and S-S end conditions

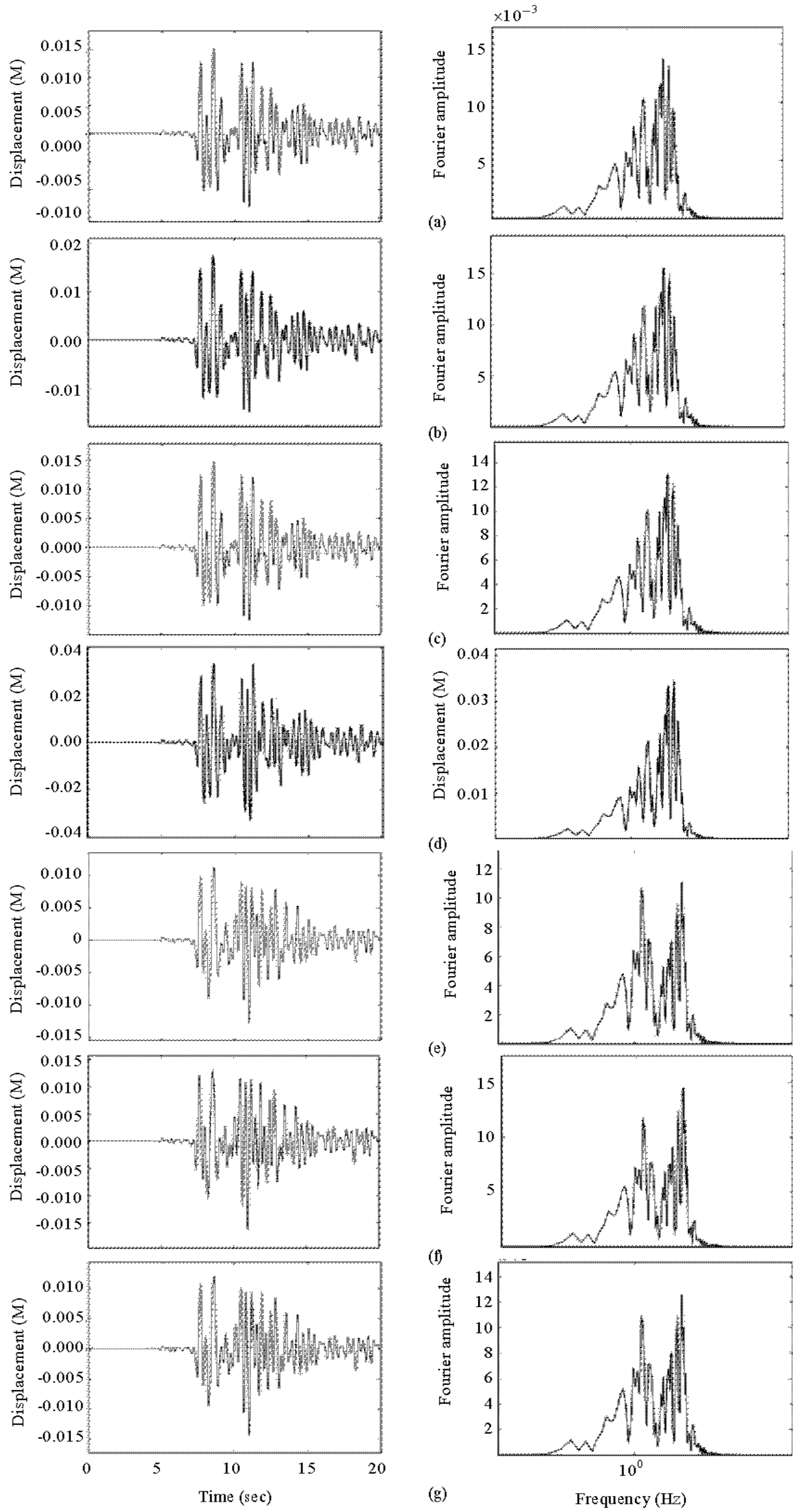

Fig. 17: Continued

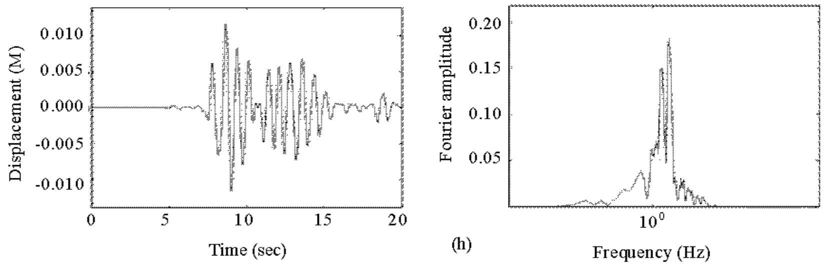

Fig. 17: Time history and Fourier amplitude spectrum of displacement response of on pipe-way piping at its various points in the case of second combination for 35% weight ratio, subjected to KJM000 component of Kobe earthquake, (a) at frame corner in the case of 8.0 mm rod and F-F end conditions, (b) at mid-span of the 70×2.6 mm pipe with 8.0 mm rod and F-F end conditions, (c) at mid-span of the 159×4.0 mm pipe with 8.0 mm rod and F-F end conditions, (d) at mid-span of the 419×6.3 mm pipe with 8.0 mm rod and F-F end conditions, (e) at frame corner in the case of 4.0 mm rod and S-S end conditions, (f) at mid-span of the 70×2.6 mm pipe with 4.0 mm rod and S-S end conditions, (g) at mid-span of the 159×4.0 mm pipe with 4.0 mm rod and S-S end conditions and (h) at mid-span of the 419×6.3 mm pipe with 4.0 mm rod and S-S end conditions

Table 6: Extreme values of displacement responses and corresponding dominant frequencies in various points of the considered combination structures

System's conditions					Response points			
Weight ratios	Pipe combination	End condition	U-bolt rod diameter (mm)	Response parameter	Frame corner	70×2.6 mm pipe mid-span	159×4.0 mm pipe mid-span	419×6.3 mm pipe mid-span
15%	1st	F-F	8.0	D_{max} (m)	-1.19E-02	-1.60E-02	-1.24E-02	
				f_{max} (Hz)	2.881	2.881	2.881	
		S-S	4.0	D_{max} (m)	-1.14E-02	-1.57E-02	-1.38E-02	
				f_{max} (Hz)	2.881	2.881	2.881	
	2nd	F-F	8.0	D_{max} (m)	1.03E-02	1.31E-02		-3.18E-02
				f_{max} (Hz)	2.588	2.588		2.588
		S-S	4.0	D_{max} (m)	8.21E-03	1.01E-02		1.11E-01
				f_{max} (Hz)	1.172	1.172		1.416
25%	1st	F-F	8.0	D_{max} (m)	-1.52E-02	-1.93E-02	-1.54E-02	
				f_{max} (Hz)	2.881	2.881	2.881	
		S-S	4.0	D_{max} (m)	-1.44E-02	-1.89E-02	-1.68E-02	
				f_{max} (Hz)	2.832	2.832	2.832	
	2nd	F-F	8.0	D_{max} (m)	1.26E-02	1.49E-02	1.23E-02	-3.22E-02
				f_{max} (Hz)	2.588	2.588	2.588	2.588
		S-S	4.0	D_{max} (m)	-9.86E-03	-1.32E-02	-1.15E-02	-1.13E-01
				f_{max} (Hz)	1.172	1.172	1.172	1.416
35%	1st	F-F	8.0	D_{max} (m)	-1.79E-02	-2.18E-02	-1.77E-02	
				f_{max} (Hz)	2.588	2.588	2.588	
		S-S	4.0	D_{max} (m)	-1.69E-02	-2.13E-02	-1.92E-02	
				f_{max} (Hz)	2.588	2.588	2.588	
	2nd	F-F	8.0	D_{max} (m)	1.53E-02	1.74E-02	1.47E-02	3.37E-02
				f_{max} (Hz)	2.295	2.295	2.295	2.588
		S-S	4.0	D_{max} (m)	-1.28E-02	-1.64E-02	-1.44E-02	-1.16E-01
				f_{max} (Hz)	2.881	2.881	2.881	1.416

response. This statement is supported by paying attention to the Fourier spectra graphs as well.

The facts pointed out for the case of 15% weight ratio, shown in Fig. 12 and 13, can be shown also in Fig. 14 and 15, which are related to 25% weight ratio as well as Figure 16 and 17, which are related to 35% weight ratio. The extreme values of displacement responses in various points of the combination structure and the corresponding dominant frequencies, shown in Fig. 12-17 are presented in Table 6.

It can be seen in Table 6 that the extreme values of displacement responses are different at various points of the combination structures, as expected. It is observed that as the softer end conditions (S-S) and U-bolt rings (with 4.0 mm diameter) are used the absolute extreme response values decrease for the cases of pipe-way frame and the 70×2.6 mm pipe in both combinations and also for the case of 159×4.0 mm pipe in the second combination, while they increase for the cases of the 419×6.3 mm pipe and the 159×4.0 mm pipe in the first combination. It is also

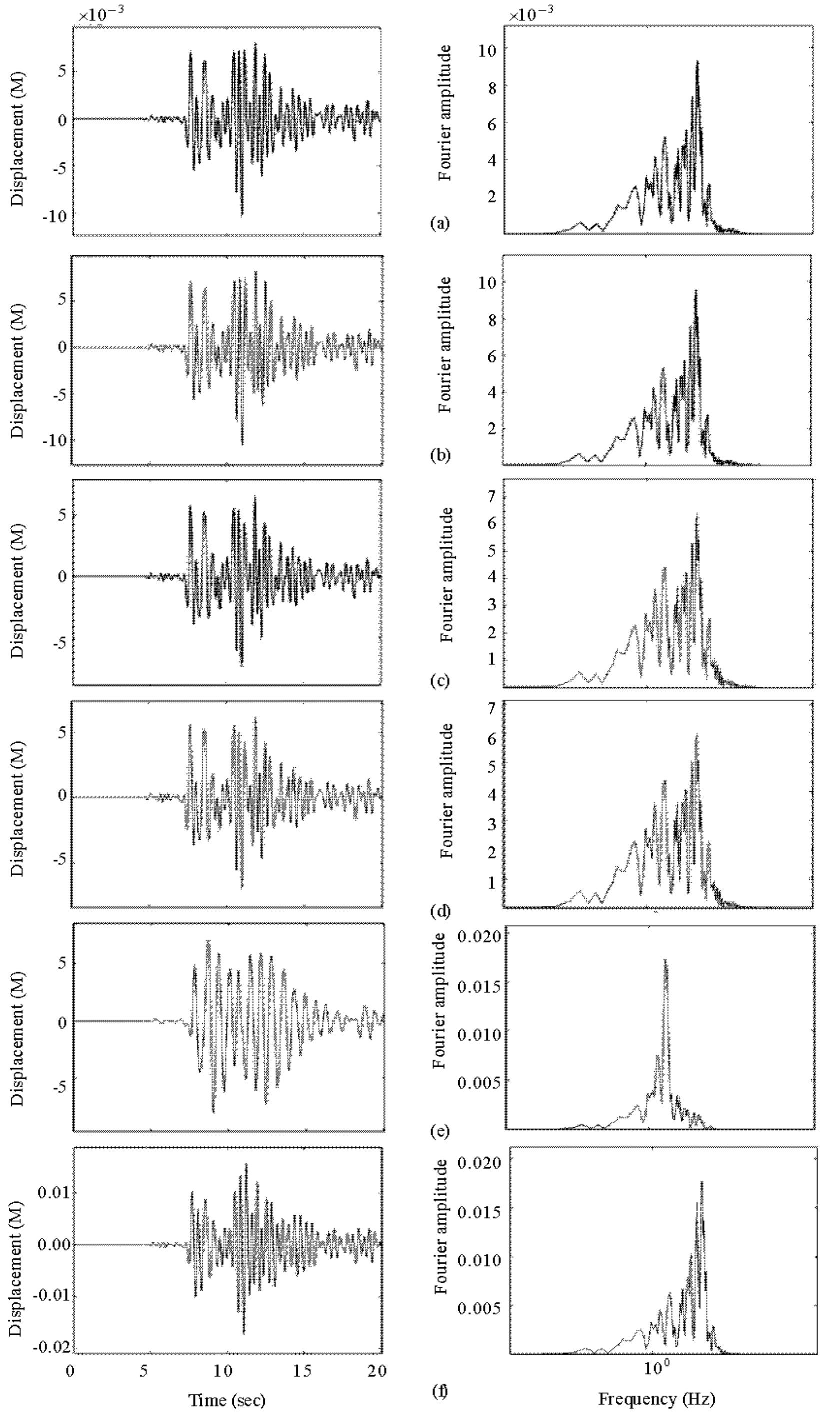

Fig. 18: Displacement response histories and corresponding Fourier spectra of the three considered pipes with F-S end conditions and U-bolt rod diameter of 4.0 and 8.0 mm, subjected to displacement time history of the pipe-way frame's top level, (a) at mid-span of the 70×2.6 mm pipe with 4.0 mm rod and F-S end conditions, (b) at mid-span of the 70×2.6 mm pipe with 8 mm rod and F-S end conditions, (c) at mid-span of the 159×4.0 mm pipe with 4 mm rod and F-S end conditions, (d) at mid-span of the 159×4.0 mm pipe with 8.0 mm rod and F-S end conditions, (e) at mid-span of the 419×6.3 mm pipe with 4 mm rod and F-S end conditions and (f) at mid-span of the 419×6.3 mm pipe with 8.0 mm rod and F-S end conditions

Table 7: The extreme values of the total displacement responses of the three considered pipes with F-S end conditions and U-bolt rod diameter of 4.0 and 8.0 mm, subjected to displacement time history of the pipe-way frame's top level and their corresponding dominant Frequencies

	Pipe dimensions (mm)					
	70×2.6		159×4.0		419×6.3	
U-Bolt rod diameter (mm)	D_{max} (m)	f_{max} (Hz)	D_{max} (m)	f_{max} (Hz)	D_{max} (m)	f_{max} (Hz)
8.0	0.0137	2.881	0.0119	2.881	0.0186	2.881
4.0	0.0136	2.881	0.0124	2.881	0.0114	1.416

Table 8: Modal frequencies of the combination structures for 15% weight ratio

Pipe combination	End conditions	U-bolt rod diameter (mm)	Mode 1st	Mode 2nd
1st	F-F	8.0	3.158	4.358
	S-S	4.0	3.085	3.348
2nd	F-F	8.0	**2.539**	4.062
	S-S	4.0	**1.319**	3.498

Bold values are modal frequencies which are close to the dominant frequencies

Table 9: Modal frequencies of the combination structures for 25% weight ratio

Pipe combination	End conditions	U-bolt rod diameter (mm)	Mode 1st	Mode 2nd
1st	F-F	8.0	**2.939**	3.720
	S-S	4.0	**2.869**	3.161
2nd	F-F	8.0	**2.512**	4.424
	S-S	4.0	**1.319**	3.222

Bold values are modal frequencies which are close to the dominant frequencies

Table 10: Modal frequencies of the combination structures for 35% weight ratio

Pipe combination	End conditions	U-bolt rod diameter (mm)	Mode 1st	Mode 2nd
1st	F-F	8.0	**2.780**	3.728
	S-S	4.0	**2.709**	3.046
2nd	F-F	8.0	**2.471**	4.455
	S-S	4.0	**1.319**	**3.010**

Bold values are modal frequencies which are close to the dominant frequencies

noticeable that as the weight ratio increases from 15% to 35% the absolute extreme displacement values increase as well at all response points, however, this increase is less remarkable for the 419×6.3 mm comparing with other pipes. These variations can be due to the ratio of the input dominant frequency to the fundamental frequencies of the combination structures; however, in the case of the 419×6.3 mm pipe the extreme response values are dependent mostly on the relative stiffness of the pipe to the U-bolt ring, regardless of the weight ratios.

Furthermore, comparing the extreme response values with their corresponding values of pipe-way and pipes, modeled as individual structures, shown in Table 4, it can be seen that there are remarkable differences between the corresponding responses and their dominant frequencies, even in the case of 15% weight ratio, however, these differences can reach up to almost 10 times in the case of the 70×2.6 mm pipe, up to almost 13 times for the 159×4.0 mm pipe and up to almost 2 times in the case of the 419×6.3 mm pipe.

To better understand the reason behind these differences and their amount for different pipes the displacement response histories and corresponding Fourier spectra of the three considered pipes with F-S end conditions and U-bolt rod diameter of 4.0 and 8.0 mm, subjected to displacement time history of the pipe-way frame's top level as the seismic input have been calculated, which are shown in Fig. 18 and the extreme values of the total displacement responses (summation of frame response and pipe response relative to frame) along with the corresponding dominant frequencies in Table 7.

It is shown in Fig. 18a-f that the general form of all response histories as well as their Fourier spectra are very similar, except for the cases of the 419×6.3 mm pipe in which the case with U-bolt rod diameter of 4.0 mm it is quite different with other cases, but for the case with U-bolt rod diameter of 8.0 mm it is less different. This is because of the higher stiffness of the latter which makes the system more similar to other combinations with the 70×2.6 mm and the 159×4.0 mm pipes. It should be pointed out that in the results shown in Fig. 12-17 and also Table 6 the interaction (stiffness and mass related effects) between pipes and pipe-way structure has been taken into account, while in the results shown in Fig. 18 this interaction has not been taken into consideration. In fact, by comparing the results of the cases with consideration of interaction and without it, it can be said that the interactive effect of relative stiffness of pipes and connecting links of pipes to the pipe-way frame, is much more on the response values than the interactive effect of masses. This statement is confirmed by comparing the results shown in Table 7 with those shown in Table 6.

For better illustration of the stiffness interactive effects and its relation with modal properties of the combination structures the first two modal frequencies of those combination structures whose responses are shown in Table 6 are shown in Table 8-10.

It is seen in Table 8-10 that in some cases, indicated by bold characters, the modal frequencies are close to the dominant frequencies of the applied used earthquake and obviously in these cases the response values are higher. By considering on the results shown in Table 8-10, as it was expected, by incrementing weight ratio the fundamental frequency decrease and due to reduction in stiffness of the system via end conditions, connecting links and pipes dimensions, fundamental frequency of the system decrease except for the first modal frequency of the systems in second combination, S-S end condition and 4.0 mm ring type. The reason behind equality of first modal frequency of those systems is presence of the 419×6.3 mm pipe with connecting links of lower stiffness in the system, which prevents participation of the pipe-way frame and other pipes in modal characteristics of the whole system. The first modal frequency of this system almost corresponds to the 419×6.3 mm pipe, considered as an Individual structure. While in the case of second modal frequency of the stated system, characteristics of all elements participated in the modal properties. It could be found out that presence of a pipe with relatively high stiffness relative to the connecting links could affect and change the whole systems dynamic properties.

Finally, from all previously presented results and discussions, it could be claimed that decoupling combination structures as to analyze individually or without consideration of interaction between primary and secondary systems could produce gross errors in evaluation and estimation of dynamic behavior of such systems. It seems that in dynamic assessment of such systems in addition to the weight ratio of secondary to primary structure, to achieve the economical and reliable retrofitting or designing of such systems, attention should be paid to the end conditions of secondary systems, relative stiffness of primary to secondary systems and also relative stiffness of secondary systems to connecting links.

CONCLUSION

Based on the numerical results it can be concluded that not only the weight percentage of piping but also the pipes' end conditions and particularly the type of connection between pipes and the pipe-way structure are also important factors affecting the whole system's behavior and may cause the system's conditions to be different from the code assumptions. In fact, it can be said that the stiffness interactive effect of pipes and connecting links of pipes to the pipe-way frame, is much more on the response values than the mass interactive effect. Therefore, it is recommended to modify the code provisions for seismic evaluation, design and retrofit of combination structures in petrochemical plants to take into account the pipe's relative stiffness to the connecting links (if there is any), end conditions and also pipe combination in the response values. Finally, it can be said that in the cases of combination structures consisted of a primary structure and single multiply-supported secondary structure the weight ratio may be an appropriate factor for making decision on inclusion or exclusion of weight interaction effects, however, in cases with multiple extended secondary structures weight ratio alone is not enough and more research is needed in this regard.

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