

SEISMIC PERFORMANCE CHARACTERIZATION OF FIRE SPRINKLER PIPING SYSTEMS THROUGH SHAKE TABLE TESTING

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ABSTRACT

Fire sprinkler systems damaged during earthquakes can compromise the functionality of a building facility either by loss of fire protection and/or by damage due to flooding. Shake table tests were conducted on a sprinkler piping specimen, with features representative of actual practices in New Zealand, to characterize its dynamic behavior under seismic floor excitation. The aim of the testing was to signify the need for a reliable procedure in the relevant New Zealand Standard (NZS 4541) for the estimation of seismic demands on these systems. The specimen was subjected to a set of motions including recorded floor acceleration response histories of an instrumented building in New Zealand. This paper first describes the test setup and the piping specimen and then discusses the seismic response of the specimen to multiple floor motions for different bracing variations. The testing showed that bracing segments of piping other than the distribution pipe modifies the dynamic characteristics of the system and consequently the seismic demands. The test results further confirm that seismic demands on pipes can be considerably greater if the system is in resonance with the floor excitation. Recommendations are provided for necessary improvements to NZS 4541 (2020) for a reliable estimation of seismic demands.

INTRODUCTION

An automatic fire sprinkler system is an essential non-structural building element, which is provided to suppress building fires to prevent loss of life and damage to property. Damage to a fire sprinkler system during an earthquake can compromise a building's fire safety, and/or may result in flooding damage due to leakage of pipes, thereby disrupting building functionality and causing damage to contents. For instance in the 2010 Chile earthquake, four hospitals were declared inoperable, and another twelve hospitals lost almost 75% of their functionality due to non-structural failures that included fire sprinkler piping [1]. The need for continuous fire-protection and functionality is critical, especially in buildings of significant importance, such as hospitals, where earthquake-related injuries need to be treated. Damage to these systems includes fractured piping connections, failure of hangers and braces, and damaged sprinkler heads due to interaction with the surrounding building elements, such as ceiling panels [1–4]. Inadequate bracing and interaction with surrounding building elements, due to insufficient clearance, have been identified as major causes of damage [1,4].

Fire sprinkler piping systems consist of a network of vertical and horizontal pipes, with hanger rods and braces to resist gravity loads and seismic demands, respectively. Generally, an intricate piping network is required to feed individual sprinklers that are spread across the plenum space. Depending on their function, pipes in a network can be of varying diameters and lengths, and are usually interconnected in different configurations as shown in Figure 1. In practice, piping networks are braced against seismic demands using proprietary braces to restrain them from deforming excessively in order to prevent leakage of connections and

prevent pounding with the surrounding building elements. This is done following a set of design provisions given in the standard for the design and installation of automatic fire sprinkler systems: NZS 4541 Automatic Fire Sprinkler Systems [5]. Table 4.11 of NZS 4541, referenced by clause 4.3.13.2.1, relates the maximum allowable lateral brace spacing for horizontal pipes of different diameters ($\leq 50\text{mm}$ to 200mm) to pipe lateral force coefficient (i.e., a measure of maximum pipe response acceleration). The technical basis for the relationship between the maximum allowable brace spacing and the lateral force coefficient is, however, not specified in NZS 4541 [5].

Given the variation in diameter, length, and plenum depth of pipes in a network attached to a building floor, the seismic demand on different segments of a piping network can vary despite being subjected to the same floor acceleration demand. For example, the displacement demand on two arm-overs with considerably different lengths attached to the same branch pipe is expected to be different. Arm-overs are critical components of a sprinkler system given that these feed individual sprinklers. The seismic vulnerability of arm-overs was evaluated by Soroushian *et al.* [6], and it is reported that long arm-overs (longer than 610mm) connected with tee fittings to branch pipes contribute dominantly to the vulnerability of piping systems to damage. Clause 4.3.13.2.2 of NZS 4541 [5] can be interpreted as stipulating lateral bracing for every horizontal pipe given that it does not provide any conditions for bracing other than the seismic coefficient and pipe diameter. However, it has been observed during surveys of buildings in New Zealand that there can be multiple arm-overs in a plenum space with different lengths, and it seems practically difficult to brace each pipe in congested

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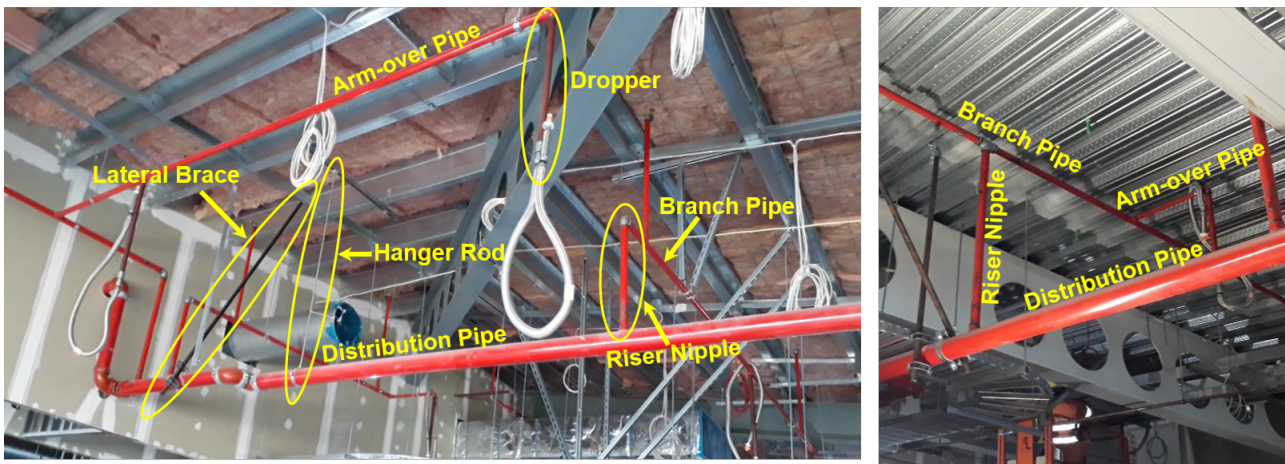


Figure 1: Segments of a sprinkler piping system: a distribution pipe is connected to the branch pipe using a riser nipple; arm-overs branch-off the branch pipe feeding the sprinkler heads connected to the end of the dropper pipes.

spaces. Arguably, it might be prudent in such scenarios not to brace an arm-over if it is ensured that the maximum displacement would not exceed the leakage threshold. It is reported by Soroushian *et al.* [4] that bracing of arm-overs might actually increase the vulnerability of their connections to damage. However, leaving an arm-over unbraced would require the provision of sufficient clearance. Since arm-overs are connected to dropper pipes that are usually attached to ceiling panels, therefore, the provision of sufficient clearance to avoid interaction is an essential requirement.

The required clearance will depend on the dynamic characteristics of an arm-over (which will depend on its length and gravity supports), its interaction with the branch pipe to which it is connected, and the frequency content of the floor excitation. However, in NZS 4541 [7], the clearance requirements were conditional upon pipe diameter, whereas in NZS 4541 [5], clearance requirements are related to the restraint condition of the surrounding building element, and are not dependent on the displacement demand on the pipe itself. This discussion signifies the need for an estimate of the actual demand on different segments of a piping network so that decisions regarding bracing of a piping segment and the determination of required brace spacing and clearance can be based on the anticipated demand rather than empirical guidelines.

Further, in addition to the intensity of a floor motion, seismic demands on a piping system are also dependent on its frequency of vibration and the frequency content of the floor excitation. If the period of vibration of a system is close to a modal period of the supporting structure, seismic demands can be considerably larger than if the system period is sufficiently far from the modal periods of the supporting structure [8]. Based on this discussion, the following two research questions are addressed in this paper:

- i. *How different bracing variations affect the seismic demand on a piping system?*
- ii. *How floor motions with different frequency content affect the seismic demand on a piping system?*

To address the research questions above, surveys of hospitals, malls and apartment buildings were conducted to identify the typical features of sprinkler piping systems in two major cities of New Zealand (Auckland and Christchurch). These surveys were complemented by considerable input from experienced industry members, and a comprehensive experimental program

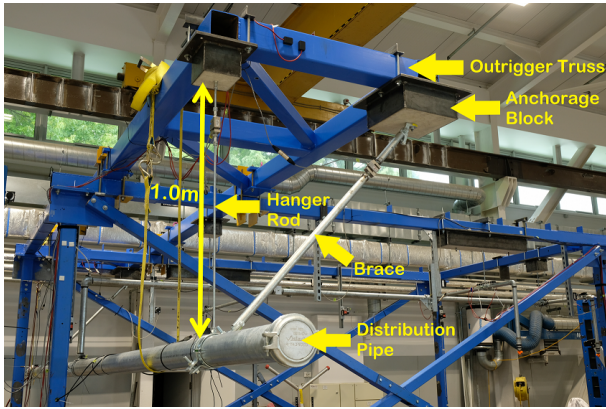
was devised at the University of Canterbury, to study the seismic response of these systems with a focus on New Zealand practices. A sprinkler piping system was configured based on the surveys and industry advice, which despite practical limits, was representative of real piping systems in scale and features. This paper first describes the test setup and the piping specimen and then discusses the seismic response of the specimen to multiple floor motions for different bracing variations.

TEST SETUP & SPECIMEN DESCRIPTION

The test setup consisted of a braced steel frame with dimensions of 4.95m (length) by 2.55m (width) by 2.63m (height) mounted on the shake table (2.0m by 4.0m). Since the braced frame could not accommodate a 6.0m long distribution pipe (half of the maximum brace spacing allowed in NZS 4541 [5]), an outrigger truss with dimensions of 6.0m (length) by 1.0m (width), was mounted on top of the braced steel frame and clamped to the roof beams of the test frame as shown in Figure 2. For the anchors of braces and hanger rods, steel boxes, made by welding individual steel plates together, were dimensioned according to the design requirements of anchors, and then filled with concrete to represent a floor slab. These concrete blocks were clamped to the outrigger truss and the roof beams of the supporting frame as shown in Figure 2.

The specimen consisted of a distribution pipe (DP) perpendicular to the direction of shaking as shown in Figures 2 and 3. The distribution pipe was connected to a branch pipe (BP) parallel to the direction of shaking, which was further connected to three arm-over pipes (APs) along its length (Figure 3). The target length of the distribution pipe was 6.0m. However, since the ends of a 65mm pipe are grooved, and need to be sealed with a grooved cap, the length of the distribution pipe was kept at 6.5m as reducing the pipe length by 500mm would require grooving the pipe ends, which was not practicable. The branch pipe was 4.77m long and was connected to the distribution pipe using a 600mm long riser nipple (Figure A1). The branch pipe was further connected along its length to three arm-over pipes of different lengths: i) arm-over pipe 1 – 1950mm, ii) arm-over pipe 2 – 1150mm, and iii) arm-over pipe 3 – 600m (Figure 3). Dropper pipes (rigid), 500m in length, were installed on all arm-overs. The cross-sectional dimensions of the pipes in the specimen are given in Table 1.

The distribution pipe was connected to the riser nipple using Victaulic Mechanical-T outlet (Figure A1). All other tee and elbow fittings in the specimen were typical threaded fittings.



(a) Side view of the test setup.



(b) Back view of the test setup.

Figure 2: Test setup for the sprinkler piping specimen.

Table 1: Cross-sectional dimensions of pipes.

Pipe	Nominal Dia. (Outer Dia. (mm))	Wall Thickness (mm)
Distribution	65 (76.1)	3.05
Branch	32 (42.4)	3.2
Arm-over	25 (33.7)	3.2
Dropper	25 (33.7)	3.2

Following the industry practice in NZ, all threaded ends of the pipes were rolled with hemp and graphite to prevent the leakage of water, and the pipes were filled with water under a pressure of 1200kPa. Threaded 10mm rods (hanger rods) were provided on both ends of the distribution pipe for gravity support (Figure 3). The branch pipe was also supported by two hanger rods along its length (Figure 3). Arm-overs 1 and 2 were provided with hanger rods near their ends for gravity support, whereas arm-over 3 was not supported by any hanger rod due to its short length, which is in line with NZ practice. The three arm-overs are shown in Figures A2, A3 and A4. The attachment components used for hanger rods and braces were typical of NZ practices and are shown in Figures A5 and A6. The 1.0m annotation on Figure 2a shows the plenum depth (herein defined as the distance between the concrete surface of the anchorage block and the top surface of the pipe) of the distribution pipe for this specimen. The plenum depths for the branch and arm-over pipes were around 400mm and 300mm, respectively.

It is important to note that the specimen was not a slice of an actual piping system, and its layout was configured as an individual system, with regard to the objectives of the test program and limitations of the shake table. In a real system, the boundary conditions of the distribution and branch pipes could be different, possibly in the form of longer lengths. Such possible variations were not an important consideration in the experimental program as the purpose of testing was to signify the influence of dynamic characteristics of a piping system and the frequency content of floor excitation on the seismic demands for a case study system.

Bracing Variations

To understand how bracing different segments of a piping network affects seismic demands on the system, the specimen was tested for different bracing variations. The distribution pipe was braced in all the cases. The bracing variations are described next.

- i. Arm-overs unbraced (Basic configuration): In the basic configuration, only the distribution pipe was braced. Branch pipe and arm-overs 1 and 2 were just provided with hanger rods for gravity support. Arm-over 3 was not supported by a hanger rod as shown in Figure A4.
- ii. Arm-overs braced: In this configuration, arm-overs 1 and 2 were braced laterally near their ends (Figure A7). All other details were similar to the basic configuration.
- iii. Branch pipe longitudinally braced: In this configuration, the branch pipe was braced longitudinally (Figure A8).
- iv. Branch pipe laterally braced: In this configuration, the branch pipe was braced laterally (Figure A9). The arm-overs were not braced.

RESPONSE MEASUREMENTS

The floor motions were input to the shake table on which the frame supporting the piping system was mounted. All the specimen response parameters will be discussed in relation to the average of the maximum accelerations measured on the longer and shorter ends of the outrigger truss (a_{LE} & a_{SE} in Figure 4a), corresponding to a shaking intensity (medium or maximum). From here onward, the average outrigger acceleration will be referred to as the floor acceleration (a_{floor}). The specimen acceleration response will be characterized by presenting and discussing the acceleration response of the distribution (a_{DP}) and branch pipe (a_{BP}). The locations of these measurements are marked in Figure 4b. In addition to accelerations, displacement response of the distribution pipe (Δ_{DP}), branch pipe (Δ_{BP}), riser nipple (Δ_{RN}), a dropper pipe ($\Delta_{Dropper}$) and the arm-overs (Δ_{AP1} , Δ_{AP2} & Δ_{AP3}) will also be discussed. The location of all these measurements is marked in Figure 4b.

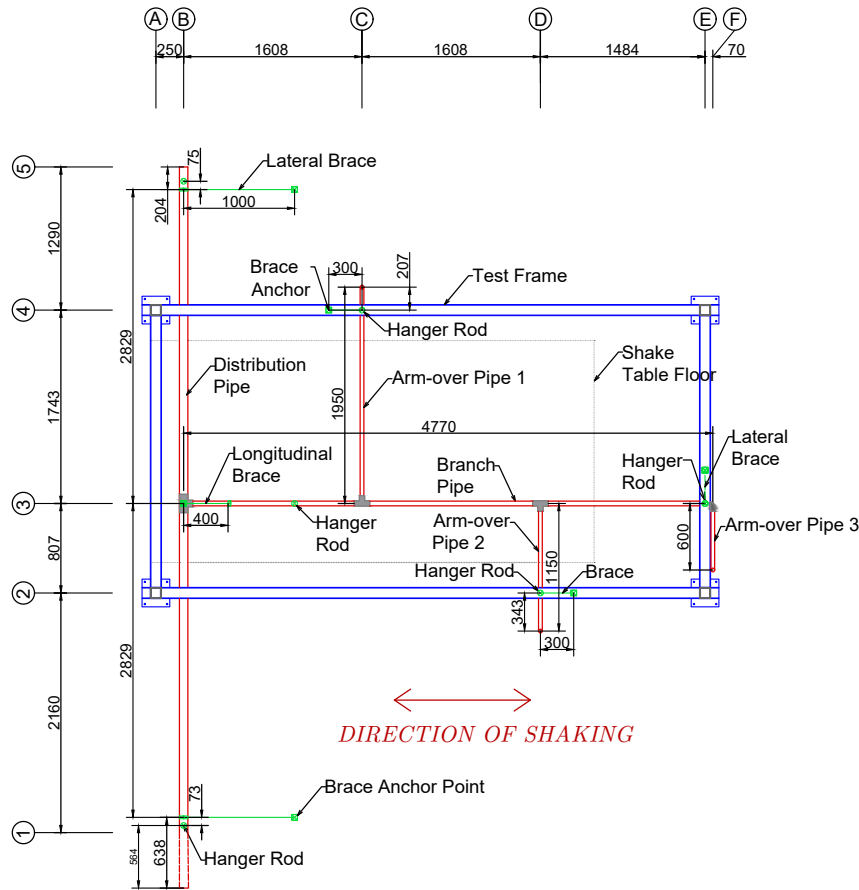


Figure 3: Plan view of the piping specimen.

TESTING & SPECIMEN RESPONSE

Input Floor Motions

The basic set of floor motions used for testing consisted of recorded floor motions and were divided into two categories: non-resonant and resonant. A non-resonant motion (NRM) is defined here as a motion in which the modal periods of the supporting structure, identified by spectral peaks in the response spectra of floor acceleration response, are not in resonance with the piping period, whereas resonant motion is defined as a motion in which the period of the specimen is in resonance with a spectral peak in the floor motion spectrum. Figure 5 shows the acceleration and displacement response spectra of the selected NRM. The period of vibration of the piping specimen, located by the dashed line, is not in proximity to the modal period of the building on which the motion was recorded (evident as a spectral peak at 0.61s). The response spectra of the selected resonant motion (RM1) are shown in Figure 5, and it can be observed that the specimen period is close to a spectral peak in the spectrum.

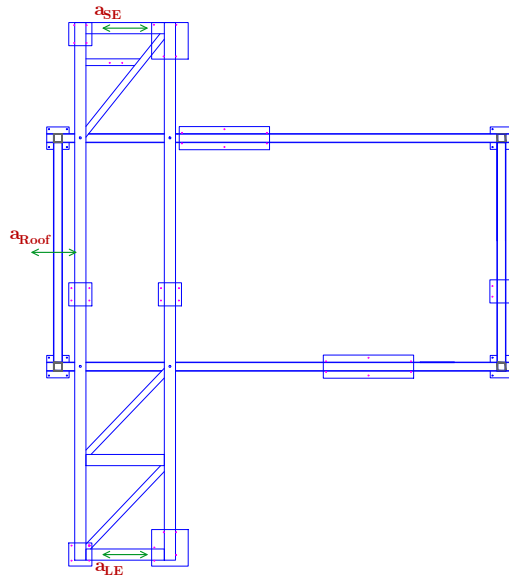
Since the specimen was undamaged at the end of the non-resonant and resonant testing, the basic set of motions was further complemented by two other motions to investigate the variability in specimen response. The third motion was a recorded resonant motion (RM2), while the fourth motion was a random motion generated to match the target spectrum in AC156 [9]. All the floor motions used were recorded during the 2010-2011 Canterbury Earthquakes on an eight-storey reinforced concrete building, UC Physics, located at the University of Canterbury, Christchurch, New Zealand.

Scaling of Motions

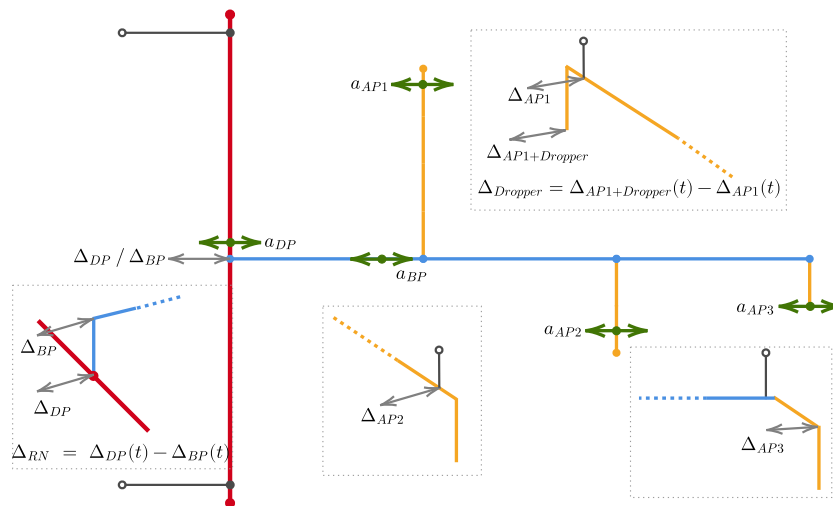
All motions were initially scaled to a peak acceleration of 0.1g. These motions were then input to the table with scale factors of 1.0, 1.5, 3.0, 4.5, 6.0, 7.5 and 8.5. The maximum capacity of the table, 1.0g, reached at the scale factor of 8.5. Thus, the maximum scale factor was selected based on the limitation of the table and not in accordance with a target shaking intensity in NZS 1170.5 [10]. The RM2 and the AC156 motion could not be scaled up beyond 0.6g, as the corresponding displacement of these motions was larger than the available stroke of the table. The response of specimen will thus be discussed for two shaking levels: i) maximum intensity, which corresponds to a table peak acceleration of around 1.0g, and includes the NRM and RM1, and ii) medium intensity, which corresponds to a table peak acceleration of around 0.5g-0.6g, and includes the response of specimen to all the four motions discussed above.

Period of Vibration of the Test Frame

As described previously, the specimen was attached to a test frame with an outrigger truss mounted on the roof of the frame. Figure 4a shows that the outrigger truss was longer on one end of the test frame compared to the other end. The periods of vibration of the test setup were determined by a white noise test. The periods were identified at 0.088s (11.4Hz), 0.1s (9.87Hz), 0.088s (11.4Hz) for the roof of the frame, longer end of the outrigger and shorter end of the outrigger, respectively.



(a) Floor acceleration measurements on the test frame roof and the outrigger truss.



(b) Piping responses measurements.

Figure 4: Acceleration and displacement response measurements.

RESPONSE OF SPECIMEN WITH UNBRACED ARM-OVERS

Specimen Free Vibration Response

To evaluate the period of vibration of the specimen along the direction of shaking, snap-back tests were conducted, which included pulling the specimen along the direction of shaking from one end (at the connection between branch pipe and arm-over 3 (Figure A10)) and then setting it in free vibration upon release. The amplitudes of the snap-back tests were 15mm and 25mm. The period of the specimen calculated from the free vibration response along the direction of shaking was 0.25s (4.0Hz). The damping ratio was also computed from the snap-back tests using the logarithmic decrement method, and the average damping values for snap-back amplitudes of 15mm and 25mm were evaluated to be 4.8% and 5.4%.

The periods of vibration of the arm-overs were determined using impact hammer testing and were found to be: 0.15s (6.66Hz) for arm-over 1, 0.09s (11.11Hz) for arm-over 2, and 0.02s (50Hz) for

arm-over 3. Some high frequency vibrations were also observed in the response of arm-overs 1 and 2, which correspond to the vibration of the dropper pipe attached to the arm-overs.

Specimen Response to Floor Motions

First, the response of the specimen to the non-resonant (NRM) and the first resonant motion (RM1) at the maximum shaking intensity will be discussed. This will then be followed by a discussion of the specimen response to all the four motions including the second resonant motion (RM2) and the AC156 motion at the medium shaking intensity.

Spectral Characteristics

This section discusses the spectral characteristics of the acceleration response of the distribution pipe as a measure of the global response. Since the floor motions were input to the shake table, their frequency content was modified at the outrigger (floor) level. Figure 6a shows the response spectrum of the accelera-

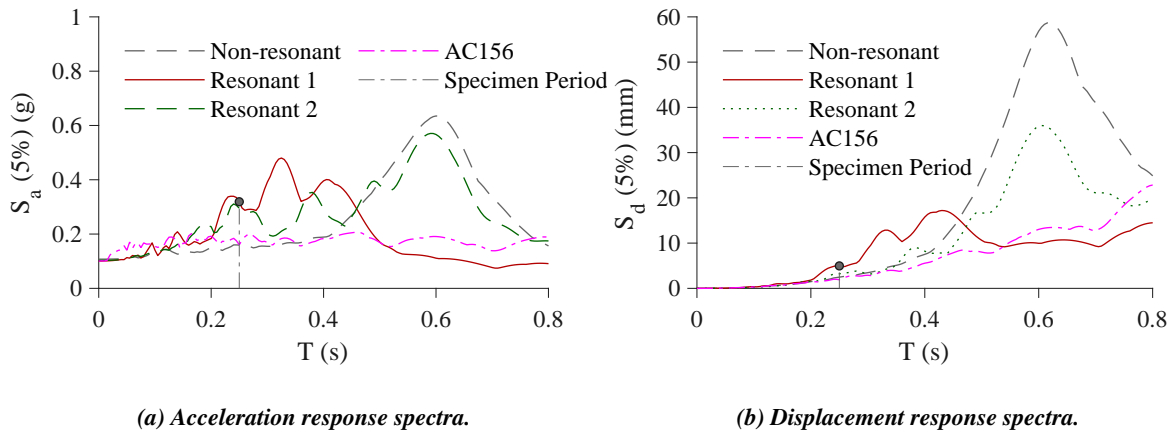


Figure 5: Acceleration and displacement response spectra of test floor motions. The vertical dashed line shows the period of vibration of the piping specimen.

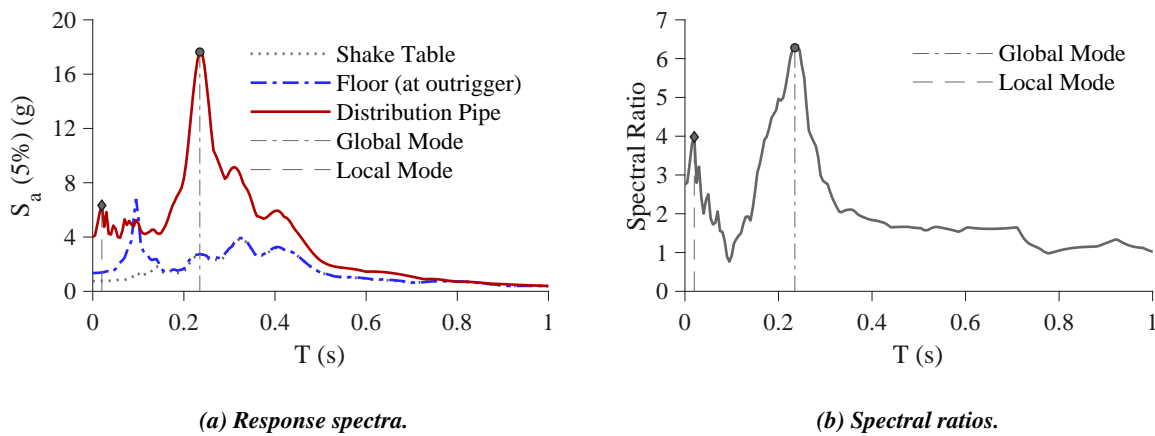


Figure 6: Response spectra and spectral ratios of the recorded acceleration responses.

tions recorded on the shorter end of the outrigger truss. The spectral peak at 0.085s (11.76Hz) identifies the period of the shorter end of the outrigger. The modification in the frequency content did not influence the objective of using non-resonant and resonant motions as the period of the piping system (0.25s) was away from the range of the periods of vibration of the test setup (0.085s to 0.095s).

The response spectrum of the accelerations recorded on the distribution pipe in response to RM1 at the maximum intensity, for a damping ratio of 5.0%, is shown in Figure 6a. The dominant spectral peak at 0.24s corresponds to the global period of the specimen. The spectral peak at 0.02s corresponds to the local mode of vibration of the distribution pipe and was further verified by an impact hammer test on the distribution pipe.

The specimen period of vibration is further verified by plotting the spectral ratios for the accelerations recorded on the distribution pipe as shown in Figure 6b. The spectral ratio is a ratio of the spectral ordinates of the accelerations recorded on the distribution pipe to the same of the shorter end of the outrigger truss. The spectral ratio plot identifies the period at 0.24s. The second spectral peak at 0.02s corresponds to the local mode of vibration of the distribution pipe.

Horizontal Acceleration Response and Dynamic Amplification

A low-pass filter with a cutoff frequency of 25Hz was used for filtering the acceleration response of the outrigger truss given that the fundamental frequency of the test setup was in the range of 10-11.4Hz. For the acceleration response of the distribution and branch pipe, a cutoff frequency of 50Hz was used for filtering to retain the high frequency response of the distribution pipe. The maximum recorded floor accelerations were 1.37g and 1.30g for the NRM and RM1, respectively. The maximum accelerations recorded on the distribution pipe were 2.56g and 4.0g for the NRM and RM1, respectively (accelerometers could not measure beyond 4.0g). The increase in the maximum acceleration is attributed to the proximity of the period of the piping specimen to a spectral peak in the RM1, as can be seen in Figure 5. A similar increase was observed in the accelerations recorded on the branch pipe.

The ratios of the maximum pipe acceleration to the maximum floor acceleration (dynamic amplification factor, DAF) were not constant, and varied with the intensity of the shaking, as shown in Figure 7, for the accelerations recorded on the distribution and branch pipe. The dynamic amplification was consistently higher for the RM1 than the NRM, which highlights the influence of the frequency content of the floor excitation. The amplification factors in response to RM1 were also higher than the maximum limit of 2.0 set for component amplification in NZS 1170.5 [10]. The values are summarized in Table 2.

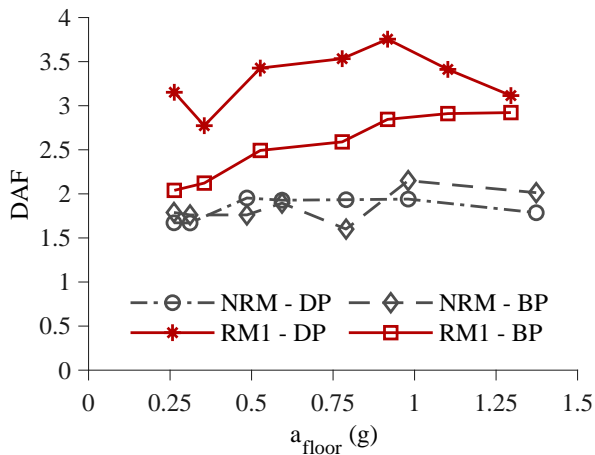


Figure 7: Dynamic amplification factors for accelerations recorded on the distribution and branch pipe.

In order to further look at the variability in specimen response, the maximum accelerations recorded on the distribution and branch pipe are compared for all the four motions in Table 3 at the medium shaking intensity. It is evident from the values reported in Table 3 that the motions scaled to the same intensity result in different response accelerations due to the relative differences in the frequency content of the motions.

Table 2: Maximum pipe accelerations & associated dynamic amplification factors at the maximum shaking intensity for the basic configuration.

Motion	Response Parameters				
	a_{floor} (g)	a_{DP} (g)	a_{BP} (g)	DAF_{DP}	DAF_{BP}
NRM	1.37	2.56	2.76	1.9	2.0
RM1	1.30	4.0	3.79	3.1	2.9

Table 3: Maximum pipe accelerations & associated dynamic amplification factors at the medium shaking intensity for the basic configuration.

Motion	Response Parameters				
	a_{floor} (g)	a_{DP} (g)	a_{BP} (g)	DAF_{DP}	DAF_{BP}
NRM	0.79	1.53	1.26	1.9	1.6
RM1	0.92	3.44	2.61	3.7	2.8
RM2	0.89	2.74	2.59	3.1	2.9
AC156	0.87	2.49	2.02	2.9	2.3

Vertical Acceleration Response

No vertical excitation was applied to the shake table, however, some significant vertical accelerations were recorded on the distribution pipe. The factors causing the vertical accelerations could possibly be the local vibration of the distribution pipe, the cantilever action of the branch pipe, and the presence of riser nipple that forced the riser nipple-branch pipe connection, and the distribution pipe, to displace vertically under horizontal excitation (Figure A11). Further, as Figure 3 shows, the test frame extended beyond the floor of the shake table to accommodate the specimen. Vertical accelerations were induced in the frame due to vibration of its cantilever portion under horizontal shaking.

These vibrations may also have induced vertical accelerations in the specimen, particularly in arm-over 3 and parts of branch pipe.

The maximum vertical accelerations recorded on the distribution pipe at the maximum intensity were 2.07g and 2.39g for the NRM and RM1, respectively. These values correspond to maximum vertical to maximum horizontal acceleration ratios of 0.8 and 0.6. It is difficult to disaggregate the recorded vertical accelerations into the different sources identified above. Nevertheless, it is recommended that the effects of vertical accelerations should be given due consideration in designing the hanger rods and braces of piping systems.

Horizontal Displacement Response

As illustrated in Figure 4b, the displacement response was measured for different segments of the tested piping network. Figure 8 shows the maximum displacements measured on different segments of the piping with increasing shaking intensity for the NRM and RM1. The differences between the maximum displacements recorded in response to NRM and RM1 increased with increasing shaking intensity. The maximum displacements of the distribution and branch pipe were 25mm and 24.7mm in response to the NRM. These displacements increased to 45.5mm and 49.5mm in response to the RM1. This highlights the significance of resonance between the supporting structure and the piping system in the determination of seismic demands. As shown previously, arm-overs 1 and 2 were supported by hanger rods near their ends. Since arm-over 3 did not have any hanger rod supporting it, it moved along with the branch pipe and the displacement demand on arm-over 3 was larger than arm-overs 1 and 2. The maximum displacement demands on different segments of the specimen at the maximum shaking intensity are reported in Table 4.

As described earlier, the distribution pipe was connected to the branch pipe using a riser nipple (600mm long). It can be inferred from Figure 9a that the riser nipple was considerably rigid, given that the displacement responses of the distribution and branch pipe were in phase. The maximum deformations of the riser nipple, calculated as the maximum difference between the displacement response histories of the distribution and branch pipe (Δ_{RN} in Figure 4b), were 6.6mm and 9.6mm for the NRM and RM1, respectively. No residual deformation or bending was apparent in the riser nipple after the test.

Figures 9b, 9c and 9d show the displacement response histories of the arm-overs superimposed on the displacement response of the branch pipe at the maximum intensity of RM1. It can be inferred from the plots that the whole system (branch pipe plus arm-overs) moved in phase at the same frequency of vibration of about 4.0Hz. Only a closer look at the response histories reveals the local troughs and peaks in the displacement response of the arm-overs, which reflect their individual characteristics. This implies that the arm-overs interacted strongly with the branch pipe and the displacement demand on arm-overs was dependent on the maximum displacement of the branch pipe. It is also evident from the plots that longer the length of an arm-over, the smaller the displacement demand on it relative to the branch pipe due to the flexibility of the arm-over.

Table 5 reports maximum displacements of the different segments of piping at the medium shaking intensity for all the floor motions. It is evident that the maximum displacements of the specimen vary in response to different floor motions scaled to the same intensity (similar floor accelerations). The NRM and the AC156 motion exerted similar displacement demands. This can be explained with reference to Figure 5, which shows that for

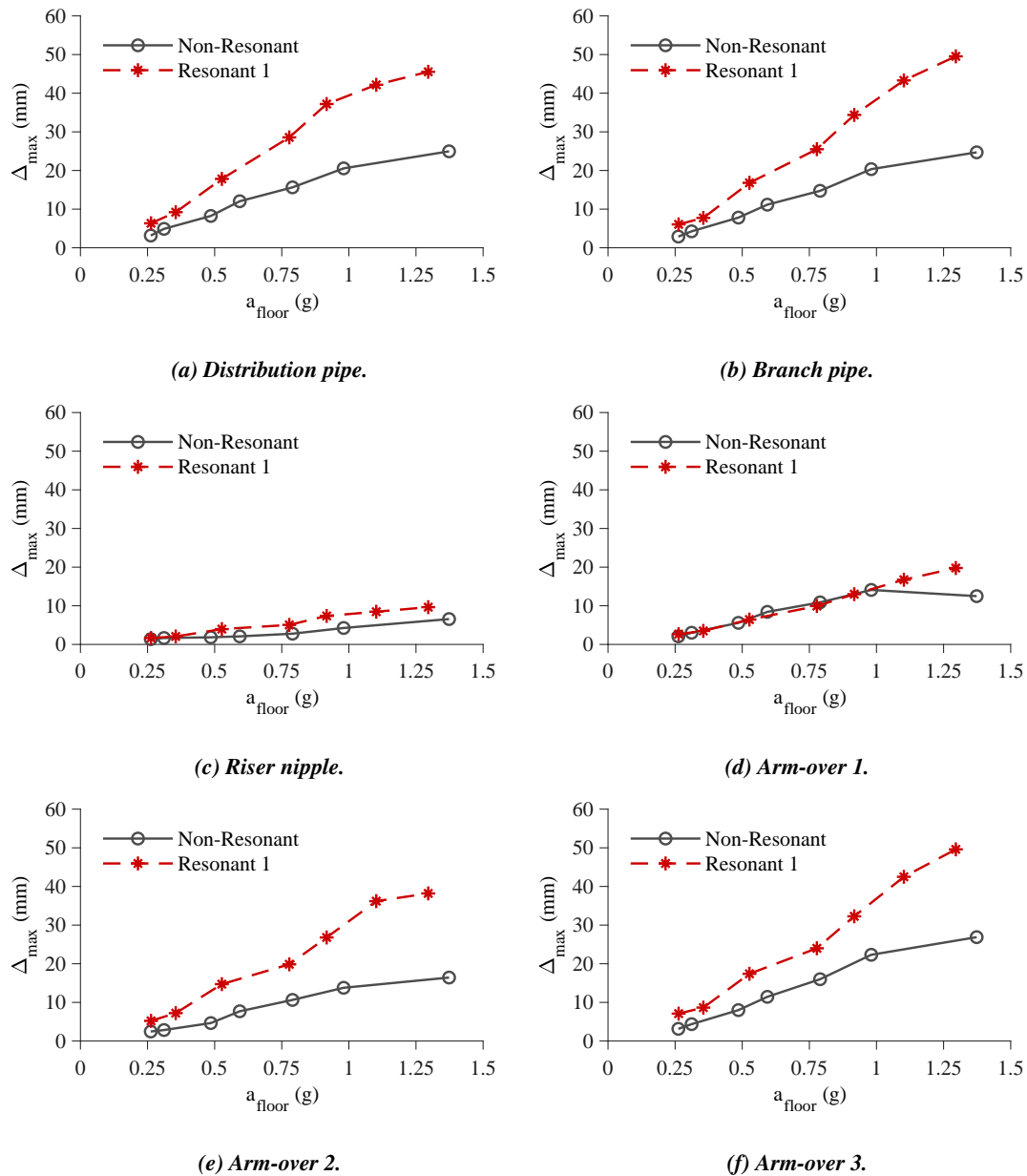


Figure 8: Maximum displacements of different segments of the piping corresponding to different shaking intensities for the basic configuration.

the specimen period of 0.25s, the spectral displacement demands (herein piping displacement demands) are similar for the two floor motions. The largest displacement demand was exerted by RM1 on all segments of the piping network.

The dropper pipe (500mm long) attached to arm-over 1 was instrumented with a string pot on its lower end to measure its deformation relative to its connection with the arm-over ($\Delta_{Dropper}$ in Figure 4b). The deformation was calculated as the maximum difference between the displacement response histories of the lower end of the dropper and arm-over 1. From the measurements, it can be inferred that the dropper was very stiff as the maximum relative deformations between the lower end of the dropper and its connection with the arm-over were 4.0mm and 5.6mm for the NRM and RM1, respectively.

In comparison, the maximum total displacements of the dropper, resulting from the flexibility of the arm-over and the dropper itself ($\Delta_{AP1+Dropper}$ in Figure 4b), were 15.1mm and 21.4mm for the NRM and RM1, respectively. This implies that the damage caused by dropper pipes due to interaction with ceiling panels is

due mainly to the displacement of the arm-overs, with which the dropper pipe moves almost rigidly.

Vertical Displacement Response

Under the applied horizontal shaking, the distribution pipe displaced along an arc rather than in a horizontal plane. The causes for the vertical response have been explained in the subsection on vertical acceleration response through the illustration in Figure A11. The maximum recorded vertical displacements of the distribution pipe for the NRM and RM1 were 5.6mm and 5.4mm, respectively.

RESPONSE OF SPECIMEN WITH BRACED ARM-OVERS

In the configuration with braced arm-overs, arm-overs 1 and 2 were braced using 10mm threaded rods (Figure A7). The period of vibration evaluated for this configuration from the snap-back test was 0.20s (5.0Hz), which is smaller than the period of the specimen in the basic configuration. This shows that arm-over

Table 4: Maximum displacements of different segments of the piping at the maximum shaking intensity for the basic configuration.

Motion	Response Parameters						
	a_{floor} (g)	Δ_{DP} (mm)	Δ_{BP} (mm)	Δ_{RN} (mm)	Δ_{AP1} (mm)	Δ_{AP2} (mm)	Δ_{AP3} (mm)
NRM	1.37	25.0	24.7	6.6	12.5	16.4	27.0
RM1	1.30	45.5	49.5	9.6	19.8	38.2	49.6

Table 5: Maximum displacements of different segments of the piping at the medium shaking intensity for the basic configuration.

Motion	Response Parameters						
	a_{floor} (g)	Δ_{DP} (mm)	Δ_{BP} (mm)	Δ_{RN} (mm)	Δ_{AP1} (mm)	Δ_{AP2} (mm)	Δ_{AP3} (mm)
NRM	0.79	15.6	14.7	2.8	10.9	10.6	16.0
RM1	0.92	37.2	34.4	7.4	13.0	26.8	32.3
RM2	0.89	29.6	32.0	4.8	11.2	18.1	30.0
AC156	0.87	14.7	16.0	5.5	8.2	11.4	17.9

bracing can shorten the global period of vibration of sprinkler systems, though its influence on period will be dependent on the length of arm-overs. The average damping ratio was 5.9% compared to 4.8% of the basic configuration for a pull amplitude of 15.0mm.

Spectral Characteristics

Bracing the arm-overs lowered the period of vibration of the specimen. The period corresponding to the dominant spectral peak in the response spectrum, shown in Figure 10a, is 0.21s for RM1, compared to 0.24s for the basic configuration. The spectral peak around 0.08s corresponds to the period of the shorter end of the outrigger truss. A third spectral peak is evident at 0.02s, which corresponds to the local mode of vibration of the distribution pipe. The spectral ratio plot in Figure 10b also identifies the global period of vibration at 0.21s. The second spectral peak, identifying the local mode of vibration, corresponds to a period of 0.02s.

Horizontal Acceleration Response and Dynamic Amplification

The maximum accelerations and dynamic amplification factors for the specimen with braced arm-overs are reported in Tables 6 and 7 for the maximum and medium shaking intensities, respectively. For the maximum shaking intensity of NRM, the peak acceleration for the braced specimen was higher than that recorded for the specimen without arm-over bracing. The peak acceleration in response to RM1 was found to be similar for both cases due to the limitation of the accelerometer in not being able to measure beyond 4.0g. No definite trend was observed in the piping acceleration between the braced and basic configuration at the medium shaking intensity.

Vertical Acceleration Response

The maximum vertical accelerations recorded on the distribution pipe for the NRM and RM1 were 2.65g and 2.71g, respectively. These are higher than the vertical accelerations recorded in the basic configuration. The ratios of the maximum vertical to the maximum horizontal accelerations are 0.9 and 0.7 for the NRM and RM1, respectively.

Table 6: Maximum pipe accelerations & associated dynamic amplification factors at the maximum shaking intensity for the configuration with braced arm-overs.

Motion	Response Parameters				
	a_{floor} (g)	a_{DP} (g)	a_{BP} (g)	DAF_{DP}	DAF_{BP}
NRM	1.22	2.93	2.81	2.4	2.3
RM1	1.30	4.0	3.90	3.1	3.0

Table 7: Maximum pipe accelerations & associated dynamic amplification factors at the medium shaking intensity for the configuration with braced arm-overs.

Motion	Response Parameters				
	a_{floor} (g)	a_{DP} (g)	a_{BP} (g)	DAF_{DP}	DAF_{BP}
NRM	0.73	1.67	1.32	2.3	1.8
RM1	0.97	3.38	2.96	3.5	3.0
RM2	0.80	2.68	1.54	3.4	1.9
AC156	0.88	2.07	1.83	2.4	2.1

Horizontal Displacement Response

Bracing the arm-overs resulted in a reduction of the maximum displacement demand on different segments of the specimen. The maximum displacement of the distribution pipe for the RM1 without arm-over bracing was 45.5mm, while the same for the braced configuration was 37.4mm. The branch pipe displacement reduced from a maximum of 49.5mm to 30.5mm for the RM1. The reductions in the displacement demand for the NRM were however not as significant: the maximum displacements of the distribution and branch pipe were reduced to 22.7mm and 18.8mm compared to 25.0mm and 24.7mm for the basic configuration. Figure 11 locates the periods of vibration of the specimen with and without arm-over bracing on the displacement response spectra of the NRM and RM1. It is evident that a reduction in the period from 0.25s to 0.20s will reduce the displacement demands on the piping system. The reduction in the demand is higher for RM1 compared to NRM due to the relative difference

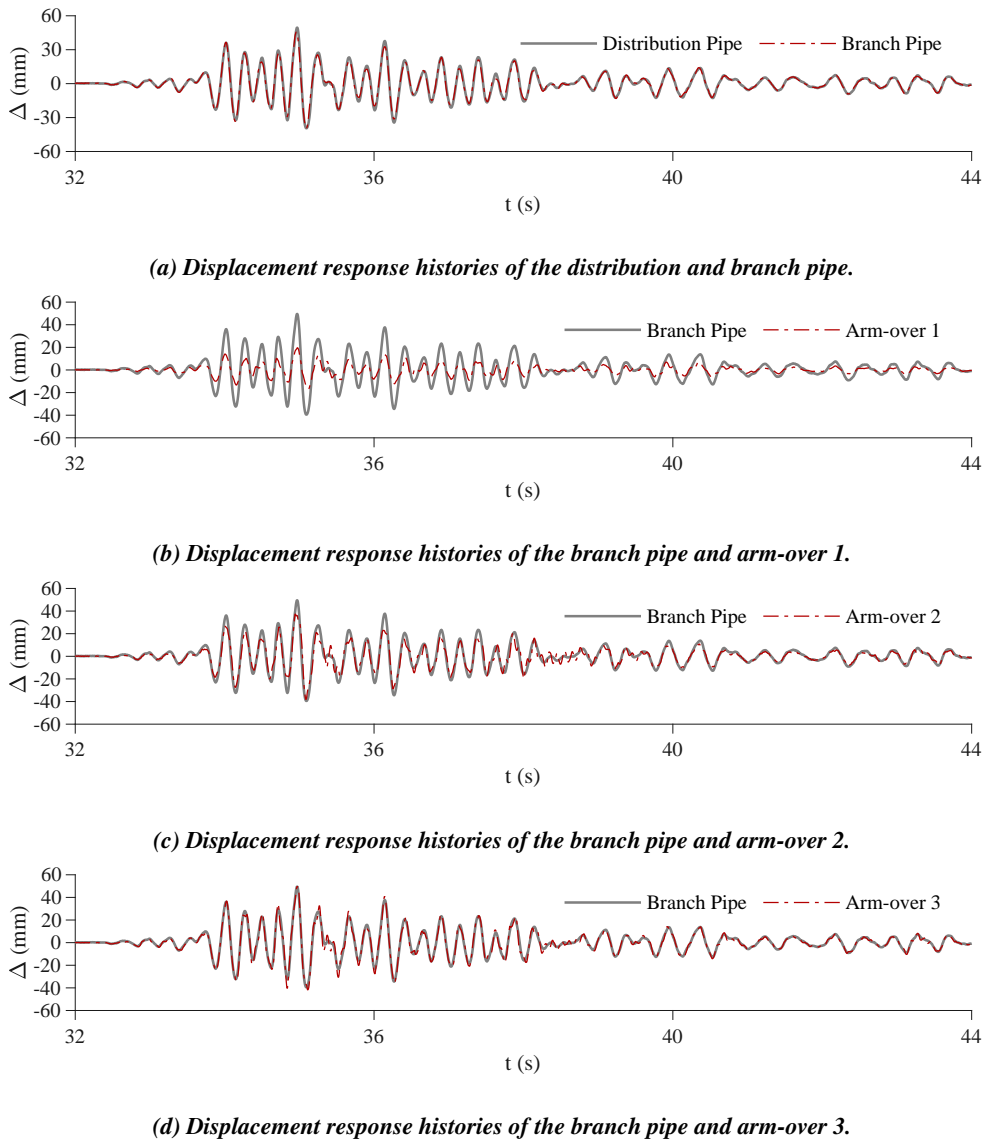


Figure 9: Displacement response histories of the different segments of piping in a curtailed time window under resonant motion I at the maximum shaking intensity.

between the spectral shapes of these motions in the period range under consideration.

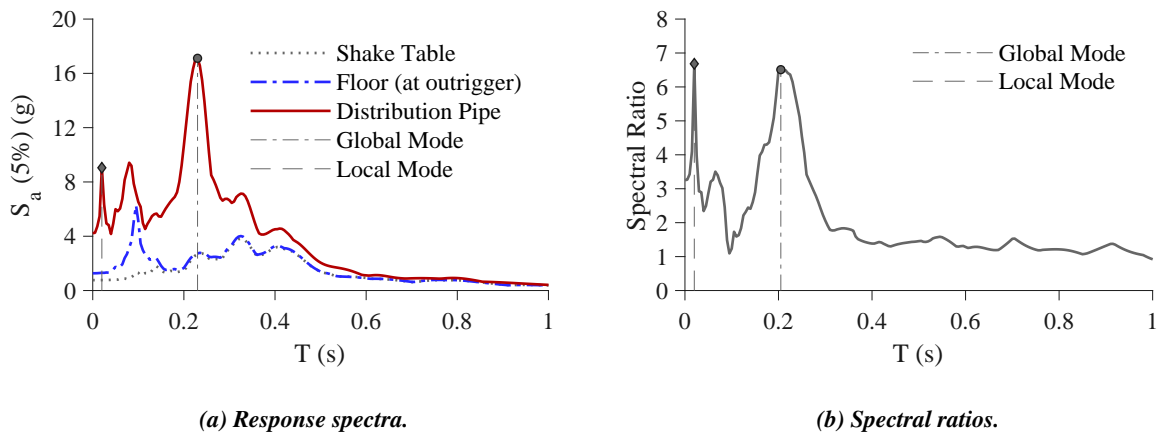
Tables 8 and 9 summarize the maximum displacements of different segments of the piping at the maximum and medium shaking intensities, respectively. It can be observed by comparing Tables 4 and 8 that the differences between the maximum displacements of the distribution and branch pipe increase with arm-over bracing compared to the basic configuration (with the demand on the higher side for the distribution pipe). The reduction in the maximum displacement of the distribution pipe due to arm-over bracing was smaller than the branch pipe; this is because the distribution pipe could deform at its connection with the riser nipple despite the bracing of arm-overs, whereas the movement of the branch pipe was dependent on the stiffness provided by the arm-overs and their end-restraint.

The increased difference between the displacements of the distribution and branch pipe also led to higher deformation of the riser nipple in comparison with the basic configuration. The maximum deformation was 14.1mm for RM1 compared to 9.6mm for the basic configuration, however, no permanent deformation was observed. The displacement demand on arm-over 3 was almost equal to the branch pipe.

The relative displacements of the lower end of the dropper pipe to its connection with arm-over 1 were 4.9mm and 6.7mm for the NRM and RM1, respectively. These displacements are marginally larger than those recorded for the unbraced arm-over in the basic configuration. This verifies that dropper pipes with a nominal diameter of 25mm are very stiff and displace almost rigidly with the arm-over to which these are connected.

Table 8: Maximum displacements of different segments of the piping at the maximum shaking intensity for the configuration with braced arm-overs.

Motion	Response Parameters				
	a_{floor} (g)	Δ_{DP} (mm)	Δ_{BP} (mm)	Δ_{RN} (mm)	Δ_{AP3} (mm)
NRM	1.22	22.7	18.8	12.0	17.0
RM1	1.30	37.4	30.5	14.1	31.0



(a) Response spectra.

(b) Spectral ratios.

Figure 10: Response spectra and spectral ratios of the recorded acceleration responses for the configuration with arm-over braces.

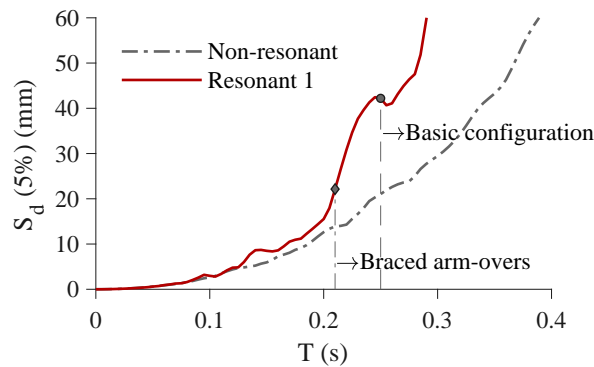


Figure 11: Spectral displacement demands on piping with and without arm-over bracing at the maximum shaking intensity for the non-resonant motion and resonant motion 1.

Table 9: Maximum displacements of different segments of the piping at the medium shaking intensity for the configuration with braced arm-overs.

Motion	Response Parameters				
	a_{floor} (g)	Δ_{DP} (mm)	Δ_{BP} (mm)	Δ_{RN} (mm)	Δ_{AP3} (mm)
NRM	0.73	13.3	10.5	6.3	10.1
RM1	0.97	28.8	21.5	11.0	19.7
RM2	0.80	21.8	15.1	7.5	14.0
AC156	0.88	14.6	11.9	7.9	10.4

Vertical Displacement Response

The maximum vertical displacements of the distribution pipe were 14.8mm and 11.1mm compared to 5.6mm and 5.4mm for the basic configuration in response to the NRM and RM1, respectively. The increase in the vertical displacement due to arm-over bracing could possibly be attributed to the increased difference between the horizontal displacements of the distribution and branch pipe, which led to higher rotation of the riser nipple due to the local deformation of the distribution pipe.

RESPONSE OF SPECIMEN WITH LONGITUDINAL BRACE ON BRANCH PIPE

In another configuration, the branch pipe was longitudinally braced with a brace assembly similar to that used on the distribution pipe (Figure A8). The arm-overs were unbraced. Tests were only conducted for the NRM at the maximum intensity to avoid over-stressing the anchors due to repeated testing. The period of vibration of the specimen shortened to 0.15s with the longitudinal brace from 0.24s for the basic configuration. However, the maximum acceleration response of the specimen did not change considerably despite the shortening of the period. This can be explained with reference to the spectral shape of the NRM that lacks any significant spectral peaks up to a period of 0.40s (Figure 5), and hence the change in period of the specimen did not affect the magnitude of spectral acceleration considerably.

The displacement demands were, however, reduced. This is evident from Figure 11, which shows that a reduction in period from 0.24s to 0.15s would lead to a reduction in the spectral displacements for the NRM. Table 10 reports the displacement demands on different segments of the piping with the distribution and branch pipe having maximum displacements of 14.0mm and 7.0mm compared to 25.0mm and 24.7mm for the basic configuration.

Since the arm-overs were connected to the branch pipe, their displacement demands were also reduced compared to the basic configuration as reported in Table 10. Particularly, the reduction in the peak displacement of arm-over 3 is notable, since due to its short length, it displaced together in a rigid manner with the branch pipe, which did not happen when the branch pipe was

Table 10: Comparison of maximum specimen responses to non-resonant motion with and without longitudinal brace on branch pipe.

Configuration	Response Parameters								
	a_{floor} (g)	a_{DP} (g)	a_{BP} (g)	Δ_{DP} (mm)	Δ_{BP} (mm)	Δ_{RN} (mm)	Δ_{AP1} (mm)	Δ_{AP2} (mm)	Δ_{AP3} (mm)
Basic	1.37	2.56	2.76	25.0	24.7	6.6	12.5	16.4	27.0
Long. braced	1.23	2.73	2.45	14.0	7.0	7.5	9.7	7.1	9.7

Table 11: Comparison of maximum specimen responses to non-resonant motion with and without arm-over bracing for the configuration with longitudinal brace on branch pipe.

Configuration	Response Parameters					
	a_{floor} (g)	a_{DP} (g)	a_{BP} (g)	Δ_{DP} (mm)	Δ_{BP} (mm)	Δ_{AP3} (mm)
Arm-overs unbraced	1.23	2.73	2.45	14.0	7.0	9.7
Arm-overs braced	1.31	3.0	2.25	13.1	5.6	10.1

braced. It should also be noted that the peak displacements of all arm-overs were larger than the branch pipe, though marginally. This signifies that longitudinal bracing of the branch pipe does not completely eliminate the displacement demand on arm-overs, and arm-overs displace individually under the influence of floor excitation. Testing for this configuration was repeated by bracing the arm-overs in addition to the longitudinal brace on the branch pipe. The period was shortened marginally to 0.145s from 0.15s. Given similar periods of vibration, the acceleration and displacement responses of the distribution and branch pipe were also found to be similar. These results are summarized in Table 11.

RESPONSE OF SPECIMEN WITH TRANSVERSE BRACE ON BRANCH PIPE

In the last configuration, the branch pipe was braced laterally to the length of the pipe, as shown in Figure A9, and subjected to the NRM at the maximum shaking intensity. The transverse brace did not affect the dynamic characteristics of the piping system as the period of vibration was evaluated to be 0.23s, which is almost the same as the basic configuration. The maximum displacements of the distribution and branch pipe were 24.5mm and 25.3mm, respectively, which are almost the same as the basic configuration. The peak acceleration recorded on the distribution pipe was 2.25g, which is smaller than the same for the basic configuration. The lateral brace did not affect the specimen response because of the type of brace assembly used: the pipe and the building attachment components were pinned and did not offer any lateral or rotational resistance.

SUMMARY OF FINDINGS

This paper reported results of shake table tests on a fire sprinkler piping system with details typical of New Zealand practices. The specimen consisted of a distribution pipe connected to a branch pipe, which was further connected along its length to three arm-over pipes of different lengths. Hence, the specimen was made up of pipes of different diameters and lengths, which were installed at different plenum depths relative to the roof of the test setup. The specimen was subjected to a set of recorded floor motions and was tested with different bracing variations. For all the bracing variations, no leakage or structural damage

was observed in any part of the piping system up to a maximum piping acceleration of 4.0g. Below is a summary of the findings that address the research questions raised in the introduction section.

1. Bracing segments of the piping specimen other than the distribution pipe, such as branch pipe and arm-overs, considerably affected the seismic demand on the system. Bracing arm-overs 1 and 2, in addition to the distribution pipe, lowered the period of the piping system to 0.20s from 0.25s for the basic configuration. Consequently, the displacement demands on the distribution and the branch pipe were also reduced; for the resonant excitation, the maximum displacements of the distribution and branch pipe were reduced from 45.5mm and 49.5mm to 37.4mm and 30.5mm, respectively. As expected, bracing restrained the movement of arm-overs 1 and 2; the demand on arm-over 3 was reduced as was the case with the branch pipe.
2. Longitudinal bracing of the branch pipe lowered the period of the specimen to 0.15s from 0.25s for the basic configuration. Consequently, the displacement demands were considerably reduced: maximum displacements of the distribution and branch pipe were 14.0mm and 7.0mm compared to 25.0mm and 24.7mm for the basic configuration. The maximum displacements of the arm-overs were also smaller than the displacements in the basic configuration. However, longitudinal bracing of the branch pipe did not completely eliminate the displacement demand on arm-overs, and arm-overs did displace individually under the influence of floor excitation.

The specimen was also tested by bracing the arm-overs while retaining the longitudinal brace on the branch pipe. This, however, did not affect the dynamic response of the specimen as the period was almost similar to the variation with unbraced arm-overs and longitudinal brace on branch pipe.

3. As another bracing variation, the branch pipe was braced laterally and the specimen was re-tested. The lateral brace did not affect the dynamic response of the specimen and was similar to the response of the basic configuration. This was due to the detailing of the brace assembly, in which the

pipe and building attachment components were pinned and thus did not offer any lateral or rotational resistance.

4. The results from testing show that seismic demands in response to a resonant motion can be considerably higher than the demands exerted by a non-resonant motion. The maximum accelerations recorded on the distribution pipe in the basic configuration were 2.56g and 4.0g for the non-resonant and resonant motion, respectively. Similar to accelerations, the displacement demands for the resonant case were also higher than the non-resonant case. For the basic configuration, the maximum displacements of the distribution and branch pipe for the resonant case were 45.5mm and 49.5mm compared to the 25.0mm and 24.7mm for the non-resonant case.
5. A comparison of the displacement demands for the non-resonant and the AC156 motion reveals that the results were not very different. Thus, use of the AC156 motion in a seismic assessment study might result in an under prediction of the actual demands due to seismic floor excitation, primarily in resonant cases. Proper judgment should be exercised in considering the AC156 motion as a representative building floor motion and in interpreting the results from its use in a seismic assessment study on non-structural elements sensitive to displacements.

RECOMMENDATIONS

1. Seismic demands on sprinkler piping systems should be estimated using a reliable yet simple procedure that can account for the dynamic characteristics of the system and the interaction between the piping system and the supporting structure. Current standards in New Zealand do not include any guidance on the determination of displacement demands on acceleration-sensitive systems that are also sensitive to displacements, for example, piping systems (discussed in detail in Rashid *et al.* [11]). Future updates to these standards should include guidance on the determination of displacement demands, such as through the specification of a floor displacement spectrum, so that design decisions regarding bracing and clearance can be made based on the dynamic characteristics of the system and anticipated demands, rather than empirical guidelines.

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Appendix to

SEISMIC PERFORMANCE CHARACTERIZATION OF FIRE SPRINKLER PIPING SYSTEMS THROUGH SHAKE TABLE TESTING

Muhammad Rashid, Rajesh P. Dhakal, Timothy J. Sullivan
and Trevor Z. Yeow

OVERVIEW

This appendix contains images of parts and segments of the piping specimen that are cited in the main body of the article.



Figure A1: Riser nipple connecting distribution pipe with branch pipe.



Figure A2: Arm-over 1.



Figure A3: Arm-over 2.

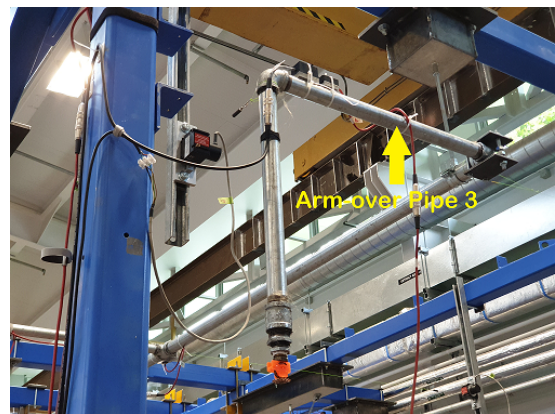


Figure A4: Arm-over 3.



Figure A5: Pipe attachment components for brace & hanger rod.



Figure A8: Longitudinal brace on branch pipe.



Figure A6: Building (anchor) attachment components for brace & hanger rod.

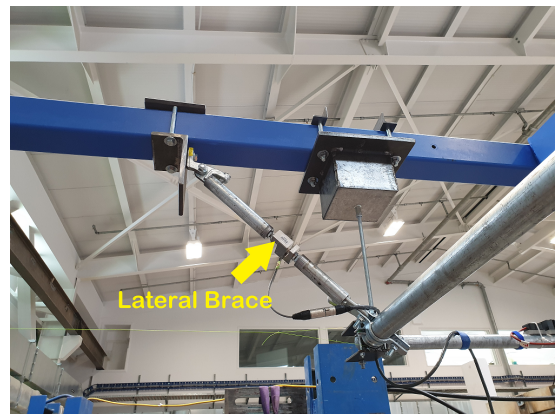


Figure A9: Lateral brace on branch pipe.

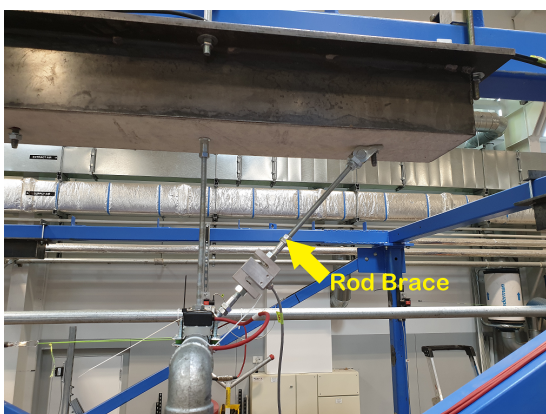


Figure A7: Threaded rod brace on arm-over 2.



Figure A10: Location of free vibration pull for snap-back test.

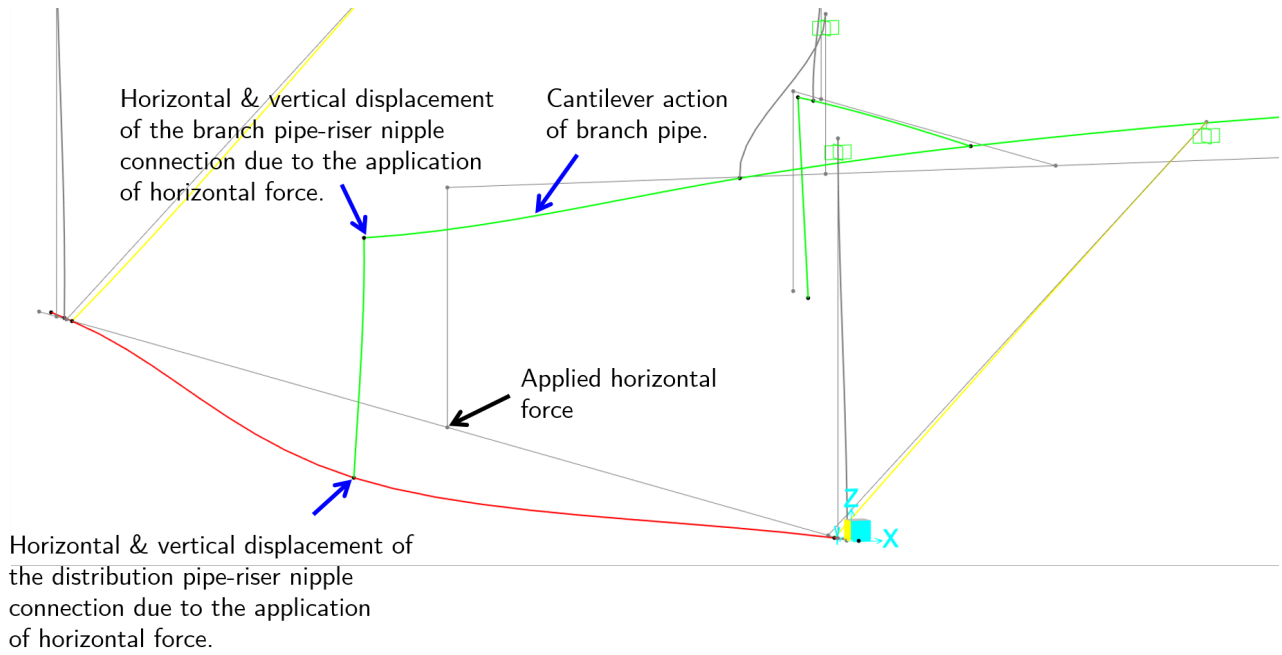


Figure A11: Deformed shape of the specimen under an applied horizontal force.