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SHAKE TABLE TESTING OF FIRE SPRINKLER PIPING SYSTEMS TYPICAL OF NEW ZEALAND PRACTICES

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Abstract

An automatic fire sprinkler piping system is an essential non-structural element which can have major impacts on both the fire safety and building functionality (e.g. flooding damage) if damaged during a seismic event. Generally, an intricate piping network is required to feed individual sprinklers which are spread across the plenum space. Depending on their function, the pipes in a network can be of varying diameters and lengths, and are usually attached to the floor at different depths relative to each other. The varying geometric and configuration details of the different segments of piping implies different dynamic characteristics, and thus a piping network subjected to a floor acceleration will have varying local seismic demands.

In practice, this elaborate piping network is braced against seismic demands using proprietary braces that are installed following a set of empirical design provisions (primarily spacing) given in the New Zealand Standard (NZS) 4541: Automatic Fire Sprinkler Systems. Relying on these provisions, the NZS 4541 requires the sprinkler system to be operational at the ultimate limit state (ULS) earthquake loading. However, the description of typical piping installation and design practices implies that bracing a random piping system using empirical design provisions, without any regard to the actual seismic demand, leads to a system whose expected global performance cannot be reliably defined. Precisely, it is not known whether the design provisions are robust enough to ensure that none of the individual segments undergo damage during design intensity shaking, which could compromise the functionality of the whole system.

To address this problem, shake table tests on sprinkler piping systems with multiple variations that are representative of actual practices are being conducted. The seismic provisions of NZS 4541 are followed when determining specimen brace locations and types. The piping specimen is mounted on a braced steel frame, and consists of a distribution pipe connected to a branch pipe through a riser nipple. The branch pipe is further connected along its length to three arm-over pipes of different lengths. The hanger rods and braces are anchored into individual concrete blocks attached to the test frame. The pipes are filled with water to monitor leakage of the piping connections during shaking. The set of input table motions include recorded floor acceleration response histories of an instrumented building in New Zealand.

This paper describes the test setup and piping configuration. An initial set of results from the ongoing experimental program are presented and their implications for the design of sprinkler piping systems in New Zealand are discussed.

Keywords: Non-structural elements; fire sprinkler piping systems; shake table tests; seismic design.

1. Introduction

An automatic fire sprinkler system is an essential non-structural element which is provided to suppress building fires to prevent loss of life and damage to property. Fire sprinkler systems consist of a network of vertical and horizontal supply piping, with hanger rods and braces to resist gravity loads and seismic demands, respectively. Generally, an intricate piping network is required to feed individual sprinklers which are spread across the plenum space. Depending on their function, the pipes in a network can be of varying diameters and lengths and are usually interconnected in different configurations. The components of the fire sprinkler system are shown in Fig. 1.

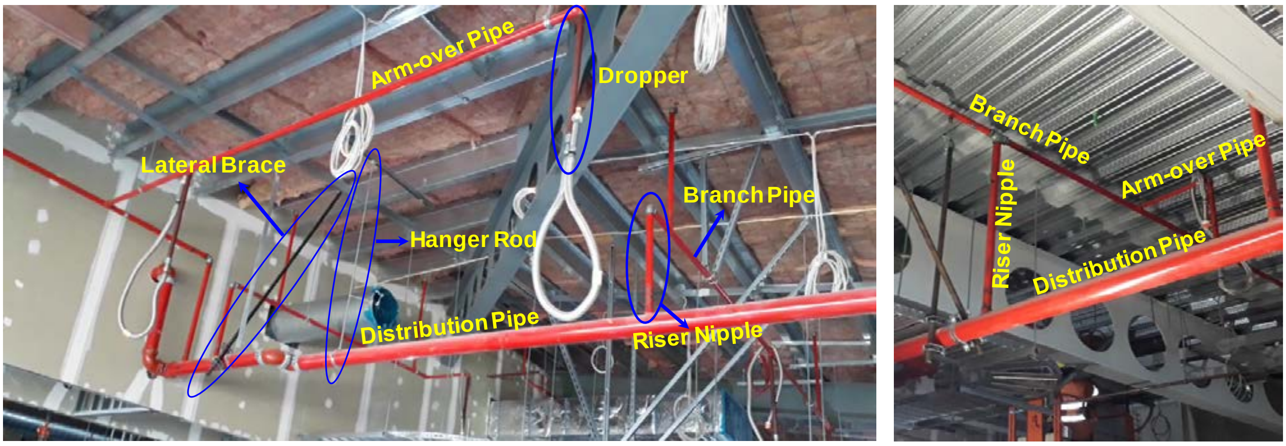
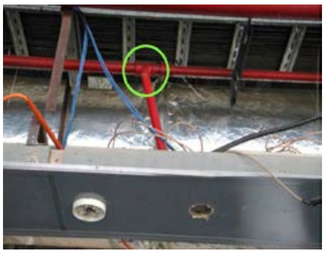


Fig. 1 – Components of a fire sprinkler piping system

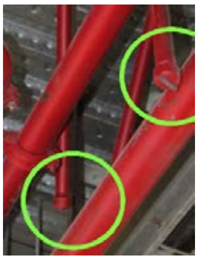
If fire sprinkler systems are damaged during an earthquake, it may not be able to work as intended afterwards which will compromise the building's fire safety, or may result in flooding damage disrupting building functionality and causing damage to contents. The latter had been observed in past seismic events, and had resulted in building impairment [4,6,10]. The need for continuous fire-protection and functionality is especially critical in buildings of significant importance, such as hospitals where severe earthquake-related injuries need to be treated.

a. Fractured elbow joint



b. Fractured tee joint

c. Sprinkler heads sheared off



d. Damaged braces

Fig. 2 – Typical damages to fire sprinkler systems [1,2,9]

Damage to these systems primarily includes fractured piping connections, failure of hangers and braces, and damaged sprinkler heads due to interaction with surrounding building elements, such as ceiling panels [3,4,6,9,10]. Examples of such damages are shown in Fig. 2. It can be inferred from Fig. 2a, 2b & 2c that damage in these systems is primarily due to interaction with surrounding elements (particularly ceilings) which can result in damaged connections (elbows & tees) and broken sprinkler heads.

In practice, piping networks are braced against seismic demands using proprietary braces to restrain them from deforming excessively in order to prevent the leakage of connections and avoid pounding with surrounding building elements. This is done following a set of design provisions (primarily spacing) given in the New Zealand Standard for the design and installation of automatic fire sprinkler systems, NZS 4541 [8]. These provisions are, however, empirical in nature and are not conditional on the seismic demand which can vary among the different segments of the same piping network (due to pipe diameter, length, configuration etc.) despite being subjected to the same floor acceleration. Relying on these provisions, the standard requires sprinkler systems to be operational at the ultimate limit state (ULS) earthquake loading defined by the New Zealand Earthquake Actions standard, NZS 1170.5 [7], for the building in which it is installed (higher for buildings of greater importance such as hospitals). This raises the question of how the expected global performance of the piping system could be reliably defined if the design was empirical in nature without explicitly considering the seismic demands. In other words, it is not known whether the design provisions are robust enough to ensure that none of the individual segments undergo damage during design intensity shaking, which could compromise the functionality of the whole system.

The performance of sprinkler piping systems have been a subject of detailed experimental and numerical investigations [5,9,10]. However, given the complex piping configurations, and the fact that these systems have not been tested with details typical of New Zealand practices, there is still considerable scope to fully understand and characterize the seismic response of NZ systems to formulate simple and validated seismic design provisions for NZS 4541 [8].

To address this problem, 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. The surveys were complemented by considerable input from industry experts to configure a piping system, which despite practical limits, is representative of real piping systems in scale and features. This basic configuration is being tested with multiple variations to simulate different realistic features under a set of input excitations that includes recorded floor acceleration response histories of an instrumented building in New Zealand. This will lead to a comprehensive set of results quantifying the seismic demands on typical sprinkler piping systems which can then be employed to rationalize the demand estimation procedures and design provisions in NZS 4541 [8]. This paper describes the test setup and the piping configuration. Initial results from the ongoing experimental program are presented and their implications for the design of sprinkler piping systems in New Zealand are discussed.

2. Test Setup and Specimen Description

The test setup consisted of a braced steel frame mounted on a shake table with dimensions of 4.95m (length) x 2.55m (width) x 2.63m (height). Since the braced frame could not accommodate a 6.0m long distribution pipe (half of the maximum brace spacing allowed in NZS 4541), an outrigger truss, 6.0m (length) x 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 Fig. 3. For braces and hanger rod anchors, steel boxes (see right side of Fig. 5), 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 frame roof beams as shown in Fig. 3.

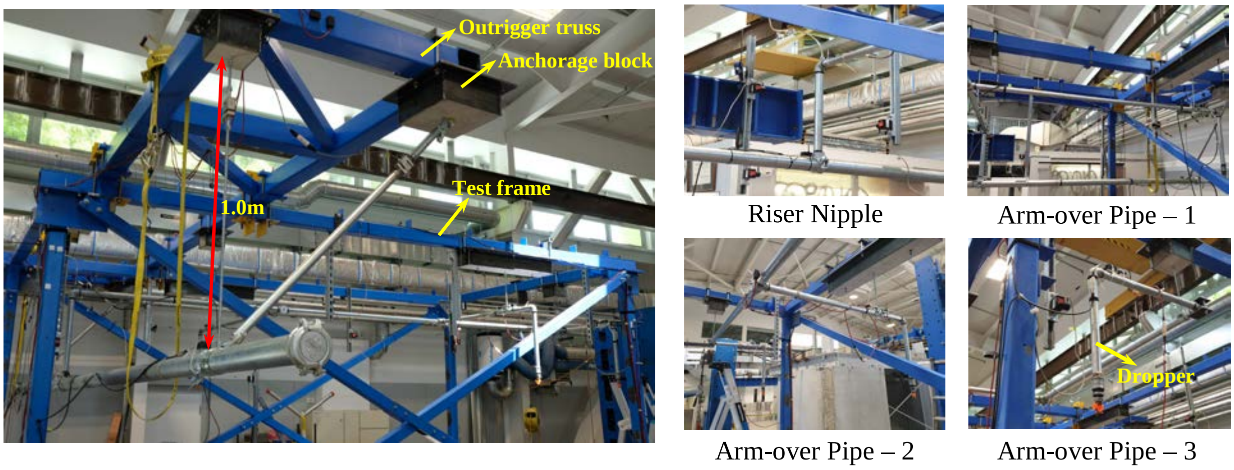


Fig. 3 – Different components of the test setup

The piping specimen consisted of a 6.5m distribution pipe connected to a branch pipe through a riser nipple and was 600mm below the branch pipe (Fig. 3). 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. 500mm long dropper pipes (rigid) were installed on all arm-over pipes. The reason for including three arm-over pipes and of different lengths is that the dropper extending from an arm-over pipe is the only component of the horizontal piping which is in direct contact with other elements such as ceiling panels and were observed to be of different lengths during surveys. Given that the current standard in New Zealand does not give sufficient guidance regarding the seismic bracing of arm-overs, it was considered important to quantify the seismic demand on these pipes. The plan view of the specimen is shown in Fig. 4 below.

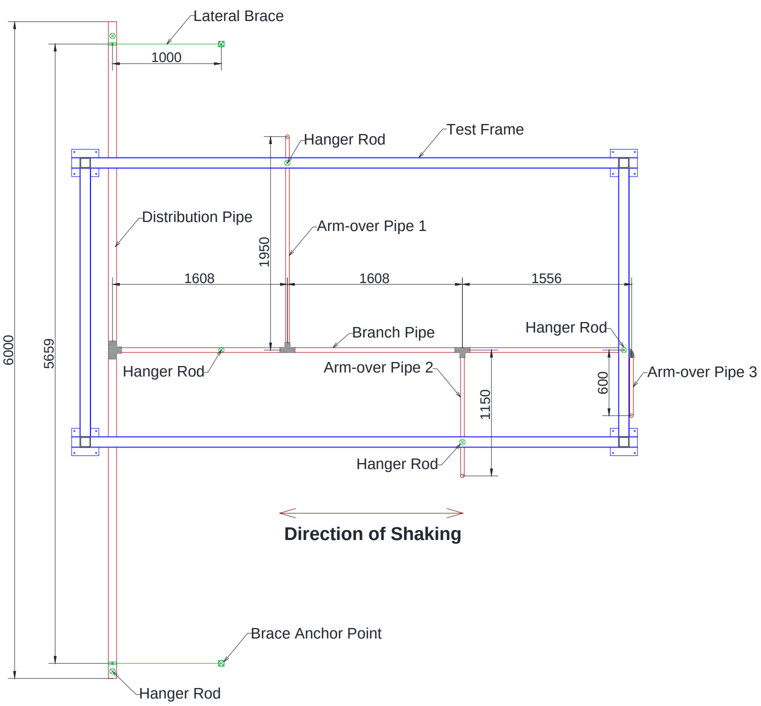


Fig. 4 – Test setup plan view

All pipes were filled with water to monitor leakage of the piping connections during shaking. Table 1 describes the cross-sectional properties of the different pipes in the specimen.

Table 1 – Piping cross-section details

Pipe	Diameter NB (*OD - mm*)	Wall Thickness (*mm*)
Distribution	65 (76.1)	3.05
Branch	32 (42.4)	3.2
Arm-over & Dropper	25 (33.7)	3.2
NB: Nominal Bore; OD: Outer Diameter		

The gravity supports for the piping system consisted of 10mm threaded rods while the braces were 25mm NB pipe sections. The anchors used for braces were HST3 M10, while for hanger rods HUS3 – I6 anchors were used.

Fig. 5 – Brace and hanger rod attachments

The distribution pipe was braced and provided with hanger rods for gravity support on both ends. The branch pipe had no lateral or longitudinal bracing and only had two hanger rods (Fig. 3). No arm-over pipe was braced in order to measure the maximum displacement demands on them. Arm-overs, 1 and 2, had hanger rods on their ends, while arm-over pipe 3 was left unsupported without any gravity support (commonly done in practice and is permitted by NZS 4541 [8]). The brace and hanger rod attachments used are shown in Fig. 5.

3. Input Excitation

The test specimen was subjected to a recorded floor acceleration response history of an instrumented eight story reinforced concrete shear wall building in New Zealand. The response spectrum of the input motion is shown in Fig. 6.

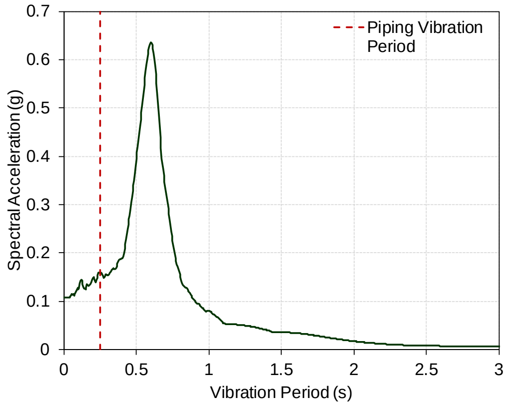


Fig. 6 – Response spectrum of input motion

This is the first of a set of different motions, targeting different frequency content, to which the specimen will be subjected. The input motion was gradually scaled until the maximum capacity of the shake table was reached.

Neither leakage nor any structural damage was observed in any part of the system up to the maximum shaking intensity that the shake table could achieve. The sections below describe the dynamic characteristics and the seismic demands on the piping resulting from the testing.

4. Specimen Response

4.1 Dynamic Characteristics

The piping natural frequency and damping were calculated using snap-back and white noise tests. The snap-back tests consisted of pulling the specimen from one end and then releasing it in order to set the specimen in free vibration. The lateral mode of vibration (along direction of shaking) has a natural frequency of 4.0Hz as shown by the power spectra (Fourier amplitude squared) in Fig. 7. The associated damping was calculated using the logarithmic decrement method and lied in the range between 4-5%.

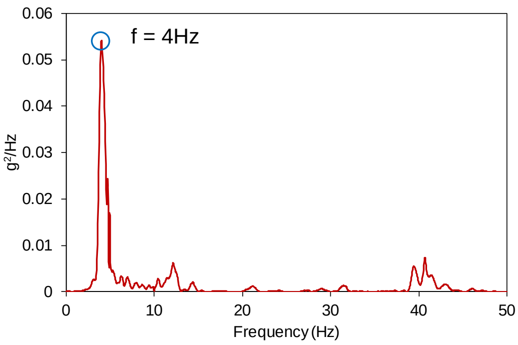


Fig. 7 – Power spectrum of distribution pipe acceleration

4.2 Acceleration Response

The input motion to the shake table was gradually scaled from 0.1g to 0.85g. The maximum acceleration recorded on the distribution piping was 2.56g. The ratio of acceleration recorded on the distribution pipe to the outrigger acceleration (amplification) varied with the intensity of the shaking as shown in Fig. 8, though this variation was not too significant.

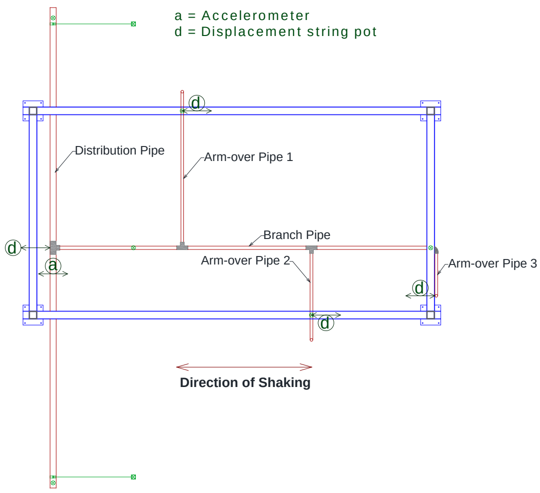
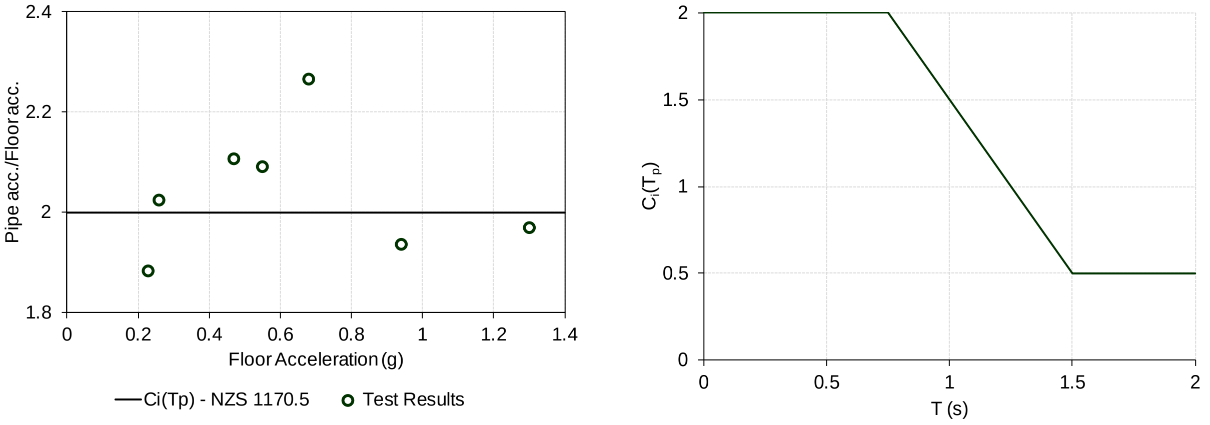


Fig. 8 – Instrument locations

The maximum and minimum values of acceleration amplification were 2.26 and 1.94 respectively. In comparison to the spectral shape coefficient ($C_i(T_p)$) given by NZS 1170.5 (a measure of component acceleration amplification relative to floor acceleration) and shown in Fig. 9b, the amplification values obtained from this test are close to the maximum value of $C_i(T_p)$ equal to 2.0 for components with vibration periods equal to or less than 0.75s.



a. b.

Fig. 9 – a) Distribution pipe acceleration amplification; b) Spectral shape coefficient [7]

It is important to note here that the vibration period of the piping (0.25s) was not in proximity to the dominant period of the input motion (0.6s) as shown in Fig. 6. Therefore, the amplification results are only representative of cases where the piping system is not in resonance with the input floor excitation. This motion was chosen intentionally to study the response of the system under non-resonant conditions. Further testing involves subjecting the specimen to a motion where the piping system is in resonance with the input motion to study the response of the system under different possible excitations.

4.3 Displacement Response

The displacement response of the different segments of the piping was measured to quantify the maximum demands and are shown in Fig. 10a & 10b. This is considered essential for the formulation of bracing requirements to restrain displacements to prevent leakage and interaction with surrounding elements. Of the three arm-overs, arm-over pipe 3 had the maximum horizontal displacement demand equal to 26.9mm. This was because unlike arm-over pipe 1 and 2, it did not have any hanger rod for gravity support, and thus moved with the branch pipe for which the maximum demand recorded was 25mm. The maximum displacements measured on arm-over pipe 1 and 2 were equal to 16.4mm and 12.5mm, respectively. Despite being longer in length, and thus more flexible, the displacement demands were less than arm-over pipe 3 due to the lateral restraint provided by the hanger rod (Fig. 3). As stated earlier, the hanger rods and their anchors remained undamaged till the end of the testing.

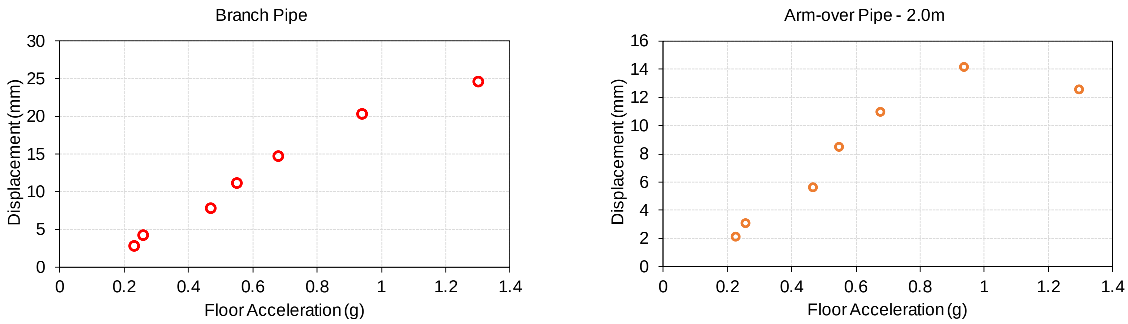


Fig. 10a – Displacement demands on different segments of piping

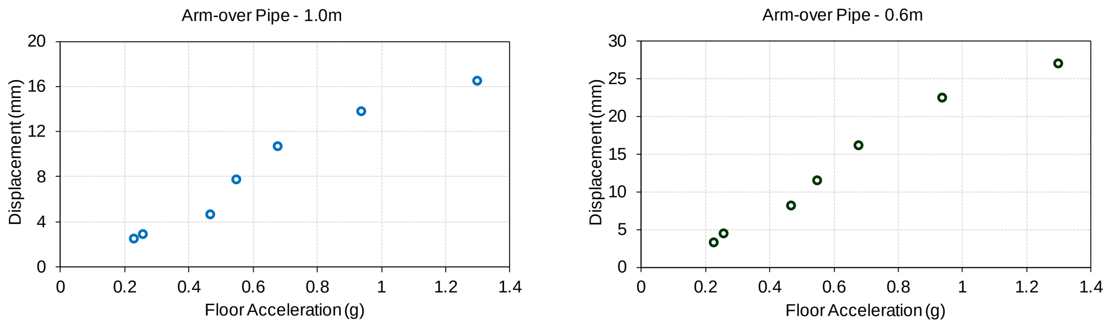


Fig. 10b – Displacement demands on different segments of piping

These results show that unbraced arm-overs can undergo displacements that might cause damage due to interaction with surrounding elements, such as ceiling panels. Traditionally, to avoid damage between a sprinkler head on a dropper pipe and the ceiling panel, a gap of 25mm in the ceiling panel is left all around the sprinkler head to avoid pounding in a seismic event. However, the test results reveal that this gap can be exceeded particularly for arm-overs without any restraint. It is worth mentioning here that these demands occurred in response to an input excitation which is not in resonance with the system. It is expected that these demands will considerably increase once the specimen is subject to a resonant motion. Additionally, future tests will also investigate how these demands vary with different piping diameters.

5. Conclusions

The experimental setup and an initial set of results from an ongoing investigation on fire sprinkler piping systems have been presented. The specimen was subjected to a floor motion recorded on a building in New Zealand and was scaled to multiple intensity levels. The maximum acceleration recorded on the distribution pipe was 2.56g and no damage was observed in any part of the system. The amplification of piping acceleration relative to floor acceleration exceeded the maximum value of 2.0 of spectral shape coefficient given in NZS 1170.5, though not considerably. Of the different piping segments, the maximum displacement demand was observed for the arm-over pipe with a length of 600mm as it was not supported by a hanger rod or brace. The observed displacement demand is important for design as the sprinkler heads, installed on droppers connected to the arm-over pipes, can interact with surrounding elements, such as ceiling panels, and cause mutual damage. The results herein were obtained using an input excitation which was characterized with a dominant period that was distant from the natural vibration period of the piping system, and thus are only representative of cases where the piping system is not in resonance with the input excitation. Ongoing tests are aiming to quantify the piping demands for resonant cases, and to investigate the influence of different piping diameters.

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