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Seismic Demands on Sprinkler Piping Systems: Findings from a Shake Table Testing Program & Relevance to NZ Standards

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Abstract. Fire sprinkler piping systems have intricate layouts on building floors that lead to complex distribution of demands in various segments of the system under seismic floor excitation. The New Zealand Standard (NZS) 4541: Automatic Fire Sprinkler Systems [2020] requires sprinkler systems to remain operational at the design limit state and provides a set of empirical analysis and design rules. One vital requirement to achieve a certain seismic performance is a reliable estimation of seismic demands. This paper aims to advance the understanding in the estimation of seismic demands on sprinkler systems to improve the reliability of designs. This objective has been achieved by conducting shake table testing on sprinkler systems typical of New Zealand practices. The investigations demonstrate that seismic demands on piping systems are significantly affected by the dynamic characteristics (period & damping) of the system as well as the frequency content of the floor excitation in addition to its intensity. Scrutiny of the test data reveals the inadequacy of design provisions in NZS 4541 [2020], such as requirements for brace forces and clearance, due to a lack of consideration for dynamic characteristics, frequency content of the floor excitation and the shaking intensity. The tests also provided valuable information on the influence of gravity supports on the dynamic response of the system and their vulnerability to failure under horizontal seismic excitation. Based on the reported findings, recommendations are provided for essential improvements to NZS 4541 [2020] to enhance the reliability of designs conducted in accordance with it.

Keywords: Seismic demands, sprinkler pipes, shake table testing.

1. INTRODUCTION

An automatic fire sprinkler system is an essential non-structural element (NSE) that is provided to suppress building fires to prevent loss of life and damage to property. 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.

Damage to fire sprinkler systems during earthquakes can compromise the fire safety of buildings and could also cause flooding damage due to leakage of pipes. Such damages could lead to a disruption in the post-earthquake occupation and functionality of buildings and damage to contents. To avoid such damage 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 avoid 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 [SNZ 2020]. Table 4.11 of NZS 4541 [2020], referenced by clause 4.3.13.2.1, relates the maximum allowable lateral brace spacing for horizontal pipes of different diameters (≤50mm 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 [2020]. In other words, it is unclear if these spacing requirements have been calibrated to any design criteria.

NZS 4541 [2020] specifies a design force equation to calculate the force demand in braces, which is given by Equation (1) below.

$$F = CW \tag{1}$$

The lateral force coefficient, C, in the above equation is given as follows:

$$C = 2.7C_H Z C_p R_c \leq 3.6 \tag{2}$$

where, W = operating weight of the component, Z = hazard factor, C_H = floor height coefficient, C_p = performance factor, and R_c = component risk factor.

Note that Equations (1) and (2) are based on another standard, NZS 4219, which covers the design, construction and installation of seismic restraints for engineering systems, such as tanks and vessels, piping, ducting, and electrical and communication systems [SNZ 2009]. The force equation in NZS 4219 is in turn a simplified version of the equation to calculate the seismic design coefficient for parts and components in NZS 1170.5: Structural Design Actions - Part 5: Earthquake Actions [SNZ 2004]. For further details, the reader is referred to Rashid *et al.,* [2021]. The coefficient 2.70 presumably accounts for the combined effect of the site hazard coefficient (C(0) in SNZ [2004]) and the dynamic amplification of piping acceleration relative to the peak floor acceleration. In addition to shaking intensity, the magnitude of piping acceleration will be dependent on the dynamic characteristics of the supporting structure and the system attached to it. However, NZS 4219 or NZS 4541 [2020] does not provide any basis for setting the coefficient value at 2.70. Multiple studies on instrumented buildings, numerical models and experimental investigations have shown that the amplifications can be well in excess of 2.0 as discussed in Rashid *et al.,* [2021]. It is not clear whether the 2.7 coefficient would lead to an underestimation or over prediction of the dynamic magnification of piping acceleration relative to the peak floor acceleration.

Additionally, the required clearance to avoid pounding with other elements around a pipe depends mainly on the dynamic characteristics of the pipe, frequency content of the floor excitation and also the movement of the surrounding element. However, in NZS 4541 [2013], the clearance requirements were conditional upon the pipe diameter and were fixed with values of 25mm and 50mm. Consequently, regardless of the demand, the values from NZS 4541 [2013] have been used in practice. This implies that design engineers did not need to estimate the displacement demand on a pipe for specification of clearance requirements. In the recent update to NZS 4541 [2013], NZS 4541 [2020] recommends horizontal clearances of 50mm, 150mm, 50mm and 25mm from restrained components, unrestrained components, penetrations and sprinklers, respectively. There is no explicit clause in NZS 4541 [2020] that requires the determination of displacement of the pipe itself in addition to the movement of the surrounding element to determine the clearances. As will be shown in this paper, the clearances in NZS 4541 [2020] could be exceeded depending on the shaking intensity and the interaction between the piping system and the supporting floor.

Bracing a piping network or providing clearances using empirical design provisions, without any regard to design criteria and the actual seismic demand, leads to a system whose expected global seismic performance cannot be reliably defined. To ensure that adequate bracing and clearances are provided to achieve target performances, it is essential that demands are based on theoretical mechanics or experimental evidence rather than empirical guidelines. To address this need, shake-table tests of sprinkler piping systems typical of New Zealand practice were performed. Results from the testing are discussed in this paper with the aim to provide useful observations on the variations of seismic demands on sprinkler systems and to encourage their possible incorporation in NZS 4541 [2020].

2.DESCRIPTION OF TEST SPECIMENS

The specimens consisted of a distribution pipe (DP) perpendicular to the direction of shaking as shown in Figure 1. The distribution pipe (6.5 m) was connected to a 4.77m long branch pipe (BP) parallel to the direction of shaking. The branch pipe was further connected to arm-over 1, 2 and 3 with lengths of 1.95 m, 1.15 m and 0.6 m, respectively (Figure 1). A total of eight specimens were tested with different variations. Herein, results from three specimens will be discussed with the major difference among these being the diameters of the distribution and branch pipes. The specimens are designated by a combination of the distribution and branch pipe diameters, such as 100-40L, which represents a specimen with a nominal diameter of 100 mm for the distribution pipe and 40 mm for the branch pipe; "L" denotes a certain variation regarding the plenum depth of the pipes, which will not be discussed here. The other two specimens are 65-32L and 40-25L. For further details on the specimen, the reader is referred to Rashid *et al.,* [2022].

a. Actual image of the specimen mounted on the test frame.

b. Back view of the specimen.

Figure 1: Details of the test specimen.

3.TEST 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 2 shows the acceleration response spectra of the selected NRM. The period range of interest, marked by the dashed lines, 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 motions, RM1, RM2, RM3 & RM4, are shown in Figure 2, and it can be observed that the period range of interest is close to the spectral peaks in the spectra. Note that the plots in Figure 2 are not the spectra of the recorded acceleration response on the roof of the test frame. These selected motions were input to the table and the resulting spectra at the roof of the test frame were modified. However, as shown in Rashid *et al.,* [2022], these differences did not affect the suitability of the motions for studying the response of the specimens to non-resonant and resonant cases.

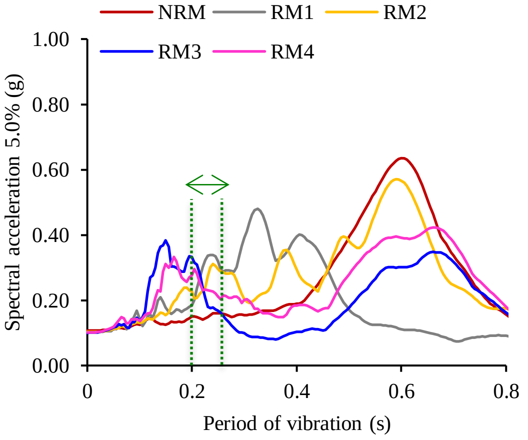


Figure 2: Acceleration response spectra of recorded floor motions selected for testing.

4.OBSERVATIONS ON SEISMIC DEMANDS

4.1 DYNAMIC CHARACTERISTICS, PIPE DIAMETER AND BRACE SPACING

The testing showed that the periods of vibration, and consequently seismic demands, were not dependent on the diameter of pipe only. The periods of vibration of the specimens along the direction of shaking were 0.21s, 0.25s and 0.22s for specimens 100-40L, 65-32L and 40-25L, respectively. The periods of specimens 100-40L and 40-25L are quite close despite the significant difference in the diameters of the constituent distribution pipes. The ratio of the unit mass of the 100 mm pipe to the unit mass of the 40 mm pipe is 3.38; the same ratio for the moment of inertia of the two pipes is 14.25. This implies that with reduction in pipe diameter, the reduction in flexural stiffness is much greater than the reduction in mass, and thus pipes with smaller diameters should have larger periods of vibration. However, the difference between periods is not significant as other sources of flexibility/stiffness were the same in the two specimens. These sources of stiffness were the brace spacing on the distribution pipe, hanger rods on the branch and arm-over pipes and the restraint provided by arm-overs. Consequently, the maximum difference between the peak displacement demands of the distribution pipe in the two specimens was approximately 10 mm as can be seen in Figure 3. Thus it can be said that two systems with the same periods of vibration and subjected to the same floor excitation, can be braced at the same spacing if the design criterion is not to exceed a certain clearance requirement. This is because the demands could be similar due to similar dynamic characteristics. However, Table 4.11 in NZS 4541 (2020) specifies different brace spacing for pipes with diameters of 100 mm and 40 mm at the same design coefficient; for example, spacing values of 7.5 m and 5.4 m are recommended for 100 mm and 40 mm pipes for a design coefficient of 3.0 g.

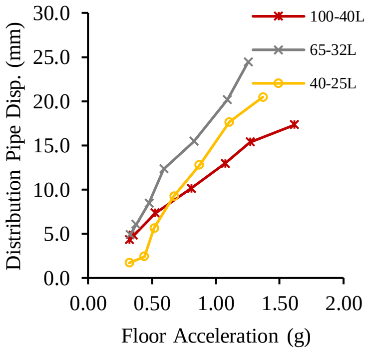


Figure 3: Comparison of the maximum recorded displacements of the distribution pipe for different specimens.

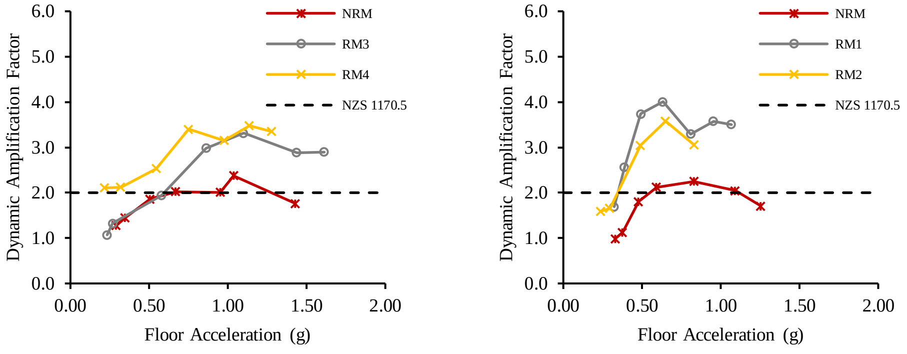
It is important to note that to satisfy the design criterion of displacements being smaller than the leakage threshold, the brace spacing could be different for the same demand as the leakage capacity of pipes of different diameters could be different. Similarly, the criterion of force demand in the brace being less than its capacity, pipes of different diameters could require different brace spacing as they have different masses. To conclude, the correct approach is to consider the dynamic characteristics and the fulfilment of design criteria at the target demands in deciding design variables, such as brace spacing.

4.2 EFFECTS OF FLOOR MOTIONS

4.2.1 Accelerations

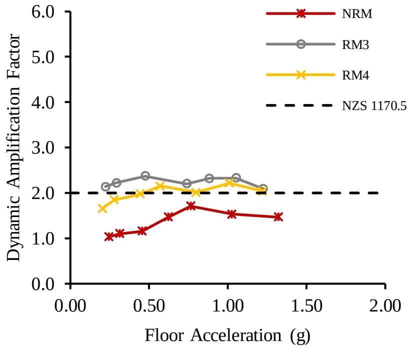
The effect of the input motion on the acceleration response of the specimens has been quantified by dynamic amplification factor, which is a ratio of the peak recorded acceleration on the distribution pipe to the peak recorded acceleration on the two ends of the outrigger truss (Figure 1). Figure 4 shows the variation of dynamic amplification factors for different motions at different shaking intensities for the acceleration recorded on the distribution pipe. The variation in the amplification factors could possibly be due to the variations in damping at different shaking intensities. In most cases, the amplification from the NRM was lower than the RMs, which proves that if there is resonance between the piping system and supporting floor, the acceleration demands would, as expected, be larger.

The maximum dynamic amplification factor for acceleration response was observed to be 3.30, 3.50 and 2.10 for specimens 100-40L, 65-32L and 40-25L, respectively. The plots in Figure 4 also show the maximum value of the spectral shape coefficient in NZS 1170.5, $C_i(T_p)$, which characterizes the dynamic amplification factor for NSEs. As stated earlier, Equation (1) is essentially based on NZS 1170.5, and no detail has been provided in NZS 4541 [2020] on what exactly is the dynamic amplification factor. Therefore, the maximum value of $C_i(T_p)$ in NZS 1170.5 has instead been used. It can be observed that NZS 1170.5 underestimates the dynamic amplification of pipe acceleration in most cases. This will have implications for the calculation of force demand in the braces, which would be larger due to higher accelerations in case of resonance. Braces on pipes could thus be under designed if the interaction between the piping system and the supporting floor is not properly taken into account.



a. 100-40L

b. 65-32L



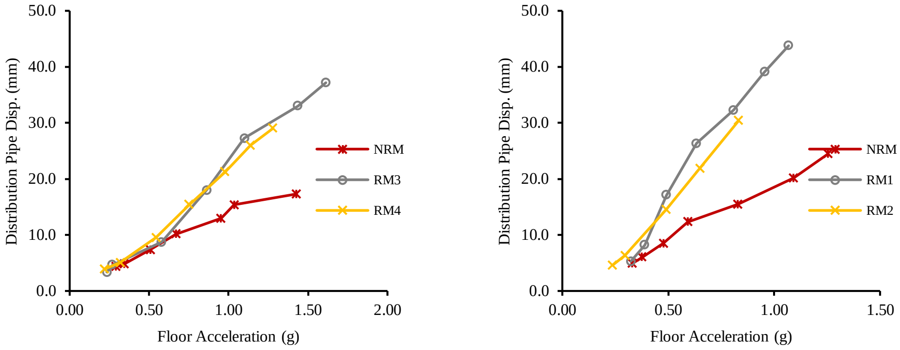
c. 40-25L

Figure 4: Dynamic amplification of the maximum recorded accelerations on the distribution pipe relative to the maximum floor accelerations at different shaking intensities.

4.2.2 Displacements

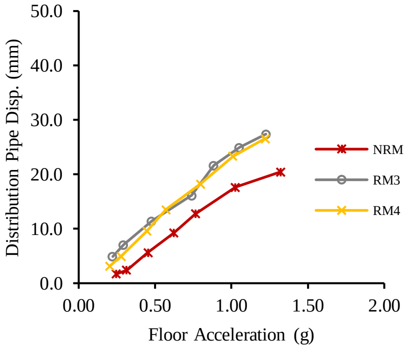
Similar to accelerations, the RMs exerted larger displacements on the specimens than the NRM as can be seen in Figure 5. The recorded displacement demands on the distribution pipe in response to RMs were found to be 2.0, 1.8 and 1.3 times that recorded for the NRM for specimens 100-40L, 65-32L and 40-25L, respectively. This implies that larger clearances would be required if the period of vibration of a piping system is closer to the modal periods of the supporting structure. The maximum displacement in response to RMs were 37.2mm, 43.8mm and 27.4mm for specimen 100-40L, 65-32L and 40-25L, respectively. It could be inferred from these values that, depending on the shaking intensity, clearance requirements of 25mm-50mm in existing systems designed to NZS 4541 [2013] could easily be exceeded, especially if the pipe and other nearby elements displace in opposite directions.

Similar argument applies to systems designed to NZS 4541 [2020] as the distribution pipe in specimen 65-32L displaced close to 50mm, which is the clearance requirement for restrained components as per NZS 4541. There are no requirements in NZS 4541 [2020] to check the specified clearance values against the displacements resulting from the design force so that the shaking intensity could be taken into account. Given that mutual interaction of sprinkler systems with other elements in the plenum space have resulted in significant damage in the past [Rashid *et al.,* 2018], the stipulation of realistic clearance requirements in NZS 4541 [2020] is highly recommended.



a. 100-40L

b. 65-32L



c. 40-25L

Figure 5: Variation of maximum recorded displacements of the distribution pipe with different input floor motions.

4.3 ROLE OF GRAVITY SUPPORTS

Figure 6 shows the deformed shape of a hanger rod on a specimen under a free-vibration pull. The hanger rods, despite being only provided for gravity support, provided partial seismic restraint due to the detailing of their attachments with the pipe and the anchor. This means that hanger rods could be vulnerable to seismic damage with serious implications for the stability of the system under gravity loads.

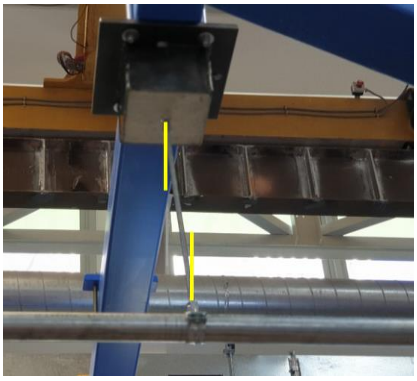


Figure 6: Deformed shape of a hanger rod on a specimen under free-vibration pull.

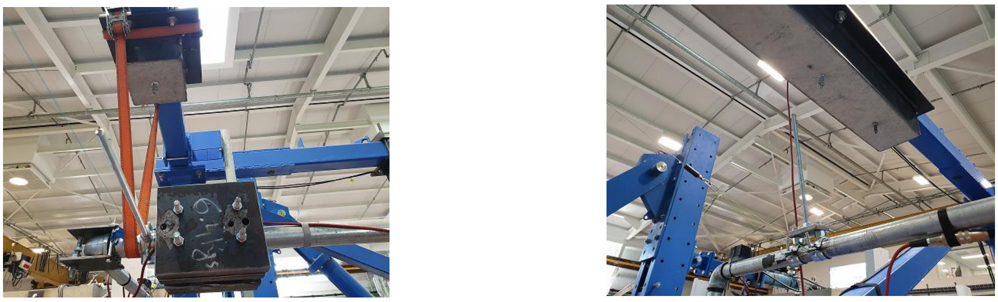
Specimen 65-32L was re-tested using the NRM after artificially increasing its mass to increase its period of vibration. The additional mass was added in the form of plates bolted to the pipes at the two sides of the distribution and branch pipe connection and along the branch pipe at multiple locations as shown in Figure 7a. The extra mass increased the period of vibration of the specimen from 0.25s to match the period corresponding to the spectral peak in the NRM at 0.61s (Figure 2). The design of hanger rods, for the increased mass, was not revised. This was because the primary target of testing was to observe the demands due to resonance with the spectral peak at 0.61s, which represented the fundamental mode of the instrumented structure. Any increase in the size of hanger rods would have increased the stiffness of the specimen, which would then have required more mass to achieve the period of 0.61s. To avoid this impracticality, testing was carried out with 10 mm hanger rods.

The maximum horizontal displacement of the distribution pipe was 145.8mm, which was almost three times higher than the previous maximum achieved with the actual mass (Figure 7b). This system, in an actual scenario, will require larger clearances than the typical values of 25-50 mm due to its own movement, and the overall clearance could be larger than 150mm if the surrounding element is unrestrained. The maximum horizontal displacements of arm-overs were also much higher than those achieved in the previous tests. From arm-over 1 to arm-over 3, the maximum displacements were 71.2mm, 145.3mm and 147.4mm, respectively. These values indicate that clearances provided around sprinkler heads on the order of 25mm will not be enough to avoid pounding with other nearby elements if the arm-overs are unbraced.

The hanger rods supporting arm-over 2 and the end of branch pipe were fractured at the maximum shaking intensity as shown in Figures 7c and 7d. Due to resonance, these rods were subjected to very high deformation demands, but it must also be kept in mind that these rods were supporting significantly higher gravity loads than would be there in an actual scenario. No other damage was observed in the system. The major lesson from these observations is that hanger rods, with the current detailing practices, should be considered during seismic design of the system.

a. Specimen 65-32L with additional lumped masses.

b. Maximum recorded displacements of the distribution pipe at different shaking intensities with and without additional mass.



c. Fractured hanger rod at the end of the branch pipe.

d. Fractured hanger rod at the end of arm-over 2.

Figure 7: Detailing, displacement response and damage modes of specimen 65-32L with additional mass.

5.RECOMMENDATIONS

This paper discussed some important results from a large testing program on sprinkler systems typical of NZ practices. Based on the observations of the experimental campaign, the following recommendations are made for future updates to NZ 4541 with regard to seismic design of suspended piping systems.

i. Brace spacing should be selected based on the fulfilment of design criteria at the estimated design seismic demands.
ii. The clearance requirements need revision and should be related to design demands of the pipe and the surrounding elements.
iii. The existing formulation in NZS 4541 [2020] for design force needs to be modified to account for the dynamic characteristics of the supporting structure and the piping system.
iv. The typical detailing of gravity supports affects the dynamic characteristics of the piping systems and hence these elements could be vulnerable to seismic damage. These elements should be considered during the seismic design of sprinkler systems. Alternatively, the attachments of the hangers should be such that the assembly only provides axial restraint and no lateral restraint.

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