THE DESIGN OF BUILDING SERVICES FOR EARTHQUAKE RESISTANCE

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SUMMARY

The design of seismic restraints for building services equipment is often a matter that is overlooked because there is no allocated design fee through a lack of coordination between the structural and building services engineers. There is therefore no formal responsibility taken for the design of the restraints and the building services contractor is often left to install "what looks right", if anything at all. Audits on five buildings showed that there had usually been an effort made to provide restraint for building services, but there were often overlooked components in the load path whose failure could still cause the whole system to fail. Laboratory shake table investigations on a selection of building services confirmed that input accelerations from the main structure would be amplified at the building services component and that it would not be sufficient to assume that the restraints could always be designed for a maximum acceleration of 1g. An introduction is given to a design guide produced by BRANZ, which provides input accelerations, determined from the complicated provisions of NZS 4203:1992, that may be used by engineers wishing to design a seismic restraint system from first principles. For building services contractors, not wishing to master the provisions of the design standard but still needing to provide an acceptable solution to the New Zealand Building Code, there is a selection of acceptable design solutions for various building services items.

INTRODUCTION

Designing appropriate seismic restraints for building services is an area of new building construction that often does not receive sufficient attention. Evidence in both New Zealand and overseas has shown that the failure of building services supports in earthquakes can have catastrophic effects such as flooding from ruptured pipe work and fire caused by shorting of electrical equipment, not to mention the lost productivity because buildings are unserviceable. The failure of building services following both the 1994 Northridge and 1995 Kobe earthquakes caused widespread disruption.

Building services covers a wide variety of non-structural components in building structures. Such items include water reticulation systems, electricity and communication reticulation systems, gas reticulation systems, heating, ventilating and air conditioning systems (HVAC), pumps, chillers, boilers, tanks, lifts, and fire sprinkler systems, to name a few.

This paper considers the applicability of existing New Zealand standards to the design of restraints for building services. It describes the relationship that exists between building services and structural engineers. The results of audits conducted on five buildings are summarised, followed by a description of laboratory tests conducted on a selection of identified problem building services installations. Finally, the paper provides a summary of the design requirements contained in a newly produced design guide for ensuring satisfactory performance of building services in an earthquake.

There appears to be a lack of financial compensation being made available to structural engineers to undertake the seismic design work for building services and to review their installation.

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EXISTING STANDARDS

The New Zealand loadings standard, NZS 4203 [SNZ,1992], contains general design loading requirements for parts and portions of buildings. The commentary to the standard includes building services equipment within the definition of parts and portions. It does state, however, that the forces determined in the standard are only applicable to the design of supports and attachments to the equipment. The provisions for determining the design forces on the attachments for the equipment are rather complicated and involve the derivation of the floor acceleration at the site of the equipment first. To accurately determine this for a building in its early structural design stage is nearly impossible and it requires a trained structural engineer to provide the service.

NZS 4203 refers the user to NZS 4219 [SANZ,1983] for the seismic design of the equipment itself. The title of the document is "Specification for seismic resistance of engineering systems in buildings" and it contains prescriptive clauses for the construction of restraint systems to resist the loads derived from NZS 4203. NZS 4219 was last revised in 1983 and since that time the philosophy of NZS 4203 has changed from dealing with working stresses to dealing with limit states. Hence, the two documents are no longer compatible.

Automatic fire sprinkler systems are considered in NZS 4541 [SNZ,1996]. This standard is at least aligned with NZS 4203. NZS 4541 contains both reference to NZS 4203 loadings which must be designed for (up to an upper limit of 1g) or alternative prescriptive provisions. Any restraint system utilising these prescriptive provisions is deemed to satisfy the loading provisions of NZS 4203. However, calculation of horizontal forces for a selection of building types from NZS 4203 indicates that the potential forces can be up to twice as much as the 1g upper limit given in the standard.

Clearly, there was a need to provide a comprehensive procedure for dealing with the seismic restraint of building services which could be used by both trained engineers having the ability to design restraints for certain loading conditions and which could also be used as a "cookbook" of safe prescriptive requirements by building services engineers and contractors

CONSULTANT SURVEYS

In order to clearly understand the relationship that exists between structural engineers and building services engineers on a new building project, four consulting engineering firms were surveyed. The level of cooperation between the two disciplines was found to be quite similar across the four firms. Except when dealing with industrial structures containing a large amount of mechanical plant, the building services engineer generally provides the structural engineer with weights and spatial requirements for plant at the preliminary stages of the contract. The structural engineer also advises the building services engineer of the positions of major structural elements such as columns and walls.

In the final design stages, the structural engineer will usually provide either/or design forces for the equipment restraints and expected interstorey displacements required to be accommodated. It is common for the building services engineer to require the installation contractor to design and certify the restraint systems for the equipment that he is installing because he may be utilising plant from a different manufacturer which still satisfies the mechanical performance specification but which has quite different physical characteristics. A difficulty often arises at this point because the contractor tends to use rules of thumb that he has established rather than employ the services of a structural engineer. Further, the current fee structure used by most consultants suggests that no seismic inspection of the completed building services installation is carried out to verify compliance.

BUILDING AUDITS

Audits of the seismic restraint systems provided for five buildings were undertaken. The building occupancies were all quite different and included a typical office building, an historic educational building, a nationally important building, a high security building and a hospital block.

For all but one of the audits, a representative from the consultancy responsible for the design of the building services for the building accompanied the author on the tour. In the other instance, a representative from the installation contractor was present.

In general terms, the quality of the seismic restraints for the services equipment was good. An effort had been made to provide restraints, either by specific design or by rule of thumb in some cases. However, often there

were items that were not properly restrained and in the event of a significant earthquake, the failure of these items would likely lead to damage to both them and other adjacent equipment. This observation particularly related to pipes, heavy cable racks and fluorescent light fittings.

Some mechanical equipment is large and can extend from one floor level nearly to the next. While base plates of pumps, boilers, heat exchangers, etc were usually well secured against earthquake attack, the associated pipe work attached to the top of these items either hung unrestrained from the storey above or if braces were provided, they arrested movement in one direction only (see Figure 1).

Also, such simple equipment as waste pipes often hung on long hangers with no lateral support provided. While these items are relatively light, they are vulnerable to fracture if unrestrained in an earthquake, rendering the waste system for the building inoperable. Even small items of equipment are just as essential to the operation of the building after an earthquake as large items and therefore deserve the same amount of consideration regarding earthquake restraint. Figure 2 shows a control cabinet, which is essential to the operation of a diesel generator for pumping fire protection water after an earthquake. The cabinet was tall and narrow, yet there were no hold-down bolts provided.

Figure 1   Insufficiently braced pipe work above pumps

Figure 2   Unrestrained control cabinet for diesel powered emergency sprinkler pump

LABORATORY STUDIES

Based on the observations made in the building services audits, three equipment set-ups were replicated in the laboratory. Each of these set-ups was installed on the BRANZ structures laboratory shake table and subjected to displacement based sinusoidal shaking to simulate earthquake attack. The set-ups included:

- A typical flexible connection between an air handling unit and a duct (these connections usually employ a canvas skirt to connect the two units)

- A typical fire sprinkler distribution network constructed in accordance with NZS 4541, and

- A pump simulation on one floor with heavy pipe work connected to it and suspended from the floor above

In all cases, initially, the equipment was excited by either a short impulse or a small displacement amplitude sinusoidal input. This was followed by short sinusoidal bursts of the shake table at accelerations of increasing size at frequencies starting at a level lower than the natural frequency of the equipment and increasing to a higher frequency.

Duct System

Both the fan coil unit and the duct system associated with it hung on 700 mm long threaded rods from a rigid frame supported on the shake table (Figure 3). Because each item had a different mass from the other and the hanger length for each was different, they oscillated at different natural frequencies. Therefore, their unbraced responses to the shake table motion were also different and often out of phase. Differential displacements reached as high as 55 mm at only 0.18g table acceleration. Recall that these items are connected by a canvas skirt. Also, at the natural frequency of the individual units, the amplification of the table acceleration was between four and five times.
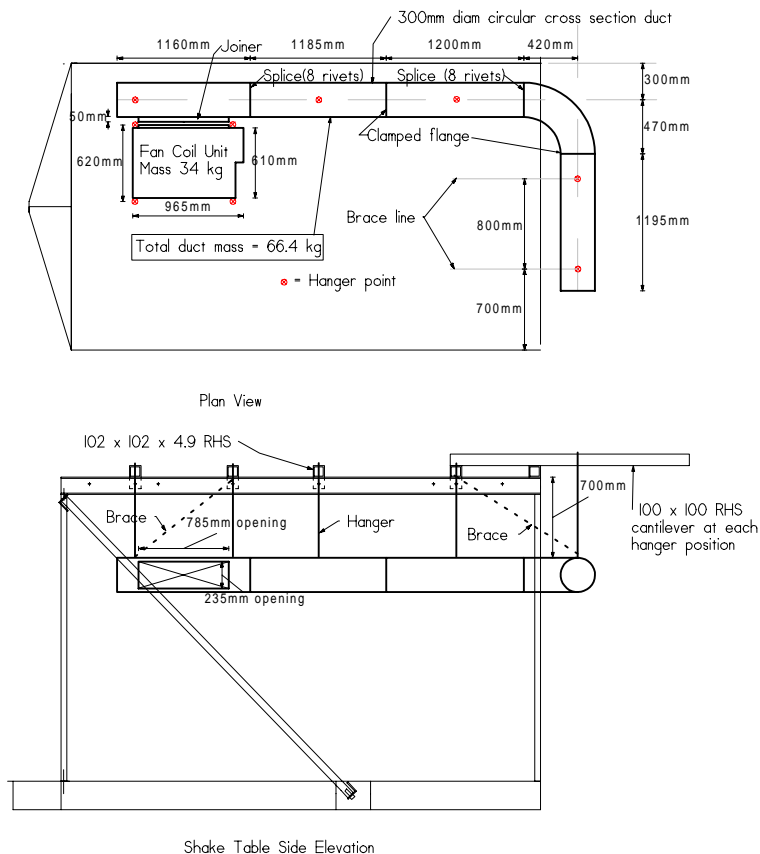
Diagonal braces were added to provide horizontal support to the elements. This addition resulted in a reduction in fan coil acceleration to about twice the table acceleration and to about the same level as the table in the case of the duct. In order to determine the forces in the braces, the table acceleration at any point in time was subtracted from the fan coil acceleration and the duct acceleration. At a table acceleration of approximately 0.75g, the differential acceleration between the table and the fan coil unit was about 0.9g. For the duct, the figure was about 1.2g.

Figure 3   Duct system set-up on shake table

The important point to note with such systems is that the skirt joints between units, provided to prevent the transfer of fan vibrations to the duct, must also be able to accommodate any differential movement between the components.

Sprinkler System

The sprinkler system set-up consisted of a 65 mm diameter main pipe with two 40 mm diameter range pipes running off the main pipe. Two additional 40 mm diameter pipe sections were fixed to each range pipe to simulate the extension of the range pipe for a normal run in practice (Figure 4). All pipes were filled with water and the network was subjected to mains water pressure

NZS 4541 requires a single lateral brace to the main pipe at a point midway between the two range pipes and in a direction parallel to the range pipes (maximum brace spacing of 6 m). At the remote ends of the range pipes, a lateral brace is required at right angles to the pipe. An allowance of the standard is that hangers less than 150 mm long may be considered as lateral braces and also longitudinal braces if they are clamped tightly to the pipe.

Figure 4   Sprinkler system on shake table

Initially, the distribution network was set-up so that the hangers for the range pipes were 150 mm long. The main pipe was positioned lower than the range pipes, as would often occur in practice. A single lateral 40 mm diameter pipe brace to the main pipe was installed midway between the range pipes. The brace employed proprietary fittings at its ends commonly used by sprinkler system installers and was attached with a 12 mm diameter expanding anchor to a slab of concrete, representing the underside of a floor slab in service. All hangers for the range pipes were 3/8" (9.5 mm) threaded rods and ½" (12.7 mm) for the main pipe. Proprietary clamps comprising two "C" sections bolted together, one with a threaded socket attached, were used to attach the pipes to the threaded rod hangers, which were in turn passed through the rolled hollow section support frame and lock-nutted.

The table was excited sinusoidally at increasing frequencies while maintaining an acceleration of 0.1 g. It appeared from the results that the system had a natural frequency of about 4 Hz. It was then subjected to short bursts of excitation at frequencies from 3 Hz up to 8 Hz in 1 Hz increments, at acceleration levels of approximately 0.3g and 1g.

At a frequency of 5 Hz and a table acceleration of 1g, the clamps securing the range pipes were observed to slide along the pipe, as the threaded rod bent at both the clamp fitting and at its connection to the supporting frame. This indicated that the 150 mm long rods had insufficient strength to resist the initial force of the pipe work. However, as one clamp slid in one direction, the other slid in the opposite direction, thus creating a triangulation in the hanger system, which had the effect of bracing the range pipes. Before the series of shakes at 1g had finished, it was necessary to replace three hangers, which had fatigued and sheared off.

The indication is that it may be better to have clamps which allow the pipe to slide through them rather than rigidly clamp the pipe, so that bracing can be achieved through the triangulation, but it cannot be guaranteed that the hangers will slide in opposite directions. At no time did any of the joints in the network leak, despite being subjected to mains pressure. However, had the safety catch slings not been present in the test, the range pipes would have fallen when the hangers fatigued and may have fractured a joint in the process.

The forces in the brace were determined by subtracting the acceleration of the pipe work at the brace from the acceleration of the shake table and multiplying by the mass of the pipe work. The lateral force on the brace was generally less than that attributable to the acceleration of the table.

The system was then lowered so that the length of the hangers for the range pipes was 300 mm. According to NZS 4541, the only change required was the installation of lateral braces at the remote end of the range pipes because the shorter hangers could no longer brace them.

As would be expected for longer hangers, the natural frequency of the network reduced to about 3 Hz. Similar observations of behaviour were made with the short bursts of table shaking when the hanger length was increased to 300 mm. Because the hangers were longer, they were unable to provide effective restraint to the range pipes, forcing all of the inertial mass of the network to be resisted by the single main pipe brace. The differential acceleration between the table and the pipes showed an increase of about 50% over the table acceleration.

An important observation made regarding the use of proprietary equipment was the need to ensure that the proprietary items are capable of withstanding the applied forces. The bracket securing the brace to the underside of the slab had a socket into which the pipe section brace fitted. The pipe was prevented from dislodging from the bracket by a single grub screw. Because the loading applied to the brace was cyclic, the grub screw worked loose and was unable to keep the pipe secured for the full series of shakes. Part way through the series it was necessary to weld the pipe into the bracket before continuing with the tests.

Pump Systems

NZS 4219 includes requirements for securing pipe work, but pipes of nominal 75 mm diameter and 100 mm diameter, not containing toxic liquids, are only required to be braced "at the points of connection of branch pipes, connections to equipment, and where the free swaying of the pipe may damage other building equipment." For pipes rising from pumps, support at the pump flange is ineffective and if there are no other building elements nearby, the standard requires no further bracing. The use of ABS plastic pipe systems is now widespread whereas at the time when the standard was written, the use of ABS was probably rare. While these materials

have some flexibility, the displacements likely to be experienced in an earthquake will cause large forces in a vertically cantilevering pipe if it is insufficiently restrained. A simulation of a pump system was set-up on the shake table (Figure 5). To model the pipe flanges normally encountered on pumps, an available heat exchanger unit with similar flanges was used, as it was essentially as stiff as a pump body. This had provision for the attachment of three pipe systems. There are often "shut-off" valves placed directly above the pump to allow servicing to take place. These can add significant weight to the vertical pipe column and introduce weak points at flange attachments. Two of the pipe systems in this test included joints to simulate the inclusion of valves. To provide a realistic mass to the system, the pipes were turned at a point below the expected soffit level of a floor above and extended as far as was practical on the shake table.

Initially, braces were installed to provide support for the pipe work above the "pumps". These were positioned parallel to the direction of table motion. The small pipe (right side in Figure 5) was braced at the furtherest hanger from the upright section while the larger pipe (centre) was braced at the hanger nearest to the upright section. The transverse pipe was braced at the only hanger supporting this pipe. Because this pipe was discontinuous, shake table motion tended to cause rotational movement of the pipe about this hanger, which would be usual if there was a large distance to the next brace.

The table acceleration was amplified by the three pipe systems to varying degrees during the shake tests. The natural frequency of the individual pipes The smaller longitudinal pipe, which rose directly from a flange on the "pump", demonstrated a reduction in the table acceleration over the test frequency range of 2 to 8 Hz. The other longitudinal pipe amplified the table acceleration by up to 1.5 times, although this increased to 2.3 times at 8 Hz. The horizontal force applied to the brace will therefore be up to 2.3 times the mass of the pipe work times the acceleration of the floor to which the pump is attached. The difference from the smaller pipe behaviour may have been caused by the flexibility created by the extra fittings and the sideways step in the larger pipe before it rose to the top turn point. At the top bend in the transverse pipe, which was free to move, the amplification was significantly more, being up to six times. No acceleration measurement was made at the brace point for this pipe, so the force in the brace could not be determined.

While the table was being excited at 0.8g at 4 Hz, the transverse pipe fractured just above the bottom flange connection (Figure 6). This may have been initiated by the presence of a small penetration for a filling tube, but such a penetration would be quite likely in service. At the same time the clamps providing gravity support to the longitudinal pipes were seen to ratchet along the pipe (Figure 6), similarly to the clamps supporting the sprinkler pipes. The effect of triangulation of the supporting system was not observed with the pump system. There was no other damage to the longitudinal pipes or their fittings during the testing series with the braces in place.

With the braces removed, each pipe was individually struck to obtain its natural frequency before the system was again excited through a range of frequencies at different table acceleration levels. The natural frequency was found to be about 4 Hz for all three pipes. As expected, the amplification of the table acceleration was significantly more that it had been for the braced pipes. Both the transverse and the large longitudinal pipes recorded accelerations of 7 times that of the table, at a 4 Hz excitation frequency. Either side of this frequency, the amplification was less. The smaller longitudinal pipe amplified the table acceleration by a maximum of only about 3 times.

There were no breakages of equipment during this series of cycling, but the pipes swung about wildly (up to ± 40 mm) on the hangers and could have easily impacted on fixed items in an earthquake. The testing again highlighted the need to ensure that pipe work is braced against lateral movement at changes of pipe direction. Further, clamps must be able to grip the pipe sufficiently tightly to prevent any slippage occurring during an earthquake.

Figure 6   Fractured pipe at flange (flange disconnected) and evidence of support bracket movement on pipe

PREPARATION OF A DESIGN GUIDE

The question arises – what needs to be included in a design guide for the seismic restraint of building services? To provide the best service, a guide needs to contain both verification procedures for satisfaction of the New Zealand Building Code (NZBC,1991) and also prescriptive acceptable solutions to the NZBC.

Should all building services items be restrained against earthquakes? NZS 4219 (SANZ,1983) contains exception cases where it is not necessary to provide seismic restraints. Such cases include pipe work below 50 mm diameter. However, the author suggests that the importance of the building and/or building service should have a significant influence over the decision on whether to brace or not, regardless of the size of the item.

The designer must give consideration to the assignment of an importance rating to the building service being restrained. Will the service be a hazard to the building occupants if it fails or will a critically important building not be able to function because the service itself fails? A matrix has been prepared to assist the designer with this decision. It considers the type of building services equipment and the occupancy of the building to arrive at risk coefficients for entry to the tables discussed below. Essentially, the greater the risk is, the greater the design load will be for the item.

The provisions in NZS 4203 (SNZ,1992) for the design of seismic restraints for building services are complex and time consuming to apply. Fee structures are generally very tight or even non-existent for designing such items, and it is therefore necessary to ensure that the design process is efficient. Until such time as NZS 4203 is revised, it is the best source of loading data applicable to New Zealand. The design guide contains tables of basic horizontal coefficients (multipliers) for determining the forces in building services restraints for a range of building types and sizes, based on the requirements of NZS 4203. These will allow the structural engineer to select coefficients without working through lengthy standard provisions. A number of assumptions have been made in the preparation of the tables to keep the calculations to a minimum. However, any error in the coefficients will be conservative. An example table layout is presented in Table 1. Clearly, it can be seen from Table 1 that the accelerations likely to be applied to building services components can be as great as 1.73g in a standard commercial building of modest height. For buildings of higher importance, the design acceleration increases to 2.25g and if the risk factor for the component is 1.1, then there is a further increase to 2.48g.

Sprinkler systems pose a high risk in that their failure may lead to the building burning down after an earthquake. Therefore, it is not considered satisfactory to limit the maximum acceleration to 1.0g, as is currently the case in NZS 4541. The recorded accelerations in the shake table investigations confirm this claim.

Unless the building service is worthy of requiring an energy dissipating system within its restraints, because it has components that cannot withstand high acceleration forces for example, it is suggested that the bracing members be designed as elastic elements. It can then be assured that there will be insignificant movement between the building service and the main structure. This is particularly important for services, such as fire sprinkler pipes, that are required to pass through the main structural members. It will be necessary to provide bracing at sufficiently regular intervals for such items as sprinkler pipes to ensure that they will not impact the main structure or other items between the restraining points. The guide gives recommended maximum spans for various pipe sizes between restraint points.

For the building services contractors who do not want to design restraints for their equipment, the guide provides acceptable solutions. These take the form of listings of ultimate strengths for strutting and tie elements at various angles and ultimate strengths for fixings, such as bolts, screws and nails.

Example calculations and designs for a selection of commonly encountered building services are also provided for ready reference by building services contractors.

Table 1   Coefficients for parts (Ductile frames on intermediate soil sites) Note that the coefficient is multiplied by the risk factor for the part to determine the total multiplier for the design of the restraint.

	Ductile Frames			Building Risk factor =		1.0		Z factor =		1.2		
					Number of Storeys							
	15	14	13	12	11	10	9	8	7	6	5	4
Storey 15	1.03											
Storey 14	1.00	0.99										
Storey 13	0.97	0.96	0.95									
Storey 12	0.94	0.93	0.92	0.93								
Storey 11	0.91	0.91	0.90	0.90	0.95							
Storey 10	0.89	0.88	0.87	0.88	0.92	0.99						
Storey 9	0.86	0.85	0.84	0.85	0.89	0.95	1.11					
Storey 8	0.83	0.82	0.82	0.82	0.85	0.92	1.05	1.17				
Storey 7	0.80	0.79	0.79	0.79	0.82	0.88	1.00	1.10	1.26			
Storey 6	0.77	0.77	0.76	0.77	0.79	0.84	0.94	1.03	1.16	1.46		
Storey 5	0.74	0.74	0.73	0.74	0.76	0.80	0.88	0.96	1.07	1.31	1.55	
Storey 4	0.71	0.71	0.71	0.71	0.73	0.76	0.83	0.89	0.97	1.17	1.36	1.73
Storey 3	0.69	0.68	0.68	0.68	0.70	0.72	0.77	0.81	0.88	1.03	1.17	1.45
Storey 2	0.66	0.66	0.65	0.66	0.66	0.68	0.71	0.74	0.79	0.89	0.98	1.16
Storey 1	0.63	0.63	0.63	0.63	0.63	0.64	0.66	0.67	0.69	0.74	0.79	0.88
Storey 0	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60

Assumption is that the roof has insignificant mass

CONCLUSIONS

This paper has shown what the problems are for the design of seismic restraints for building services equipment. It shows that it is often a matter of no allocated design fee through a lack of coordination between the structural and building services engineer and therefore no responsibility taken for the design of the restraints. Instead, the building services contractor is often relied on to provide bracing using his experience of "what looks right", with no engineering input. Building audits showed that there was generally an effort made to provide restraint to building services, although there were often overlooked components in the load path whose failure could still cause the whole system to fail. Laboratory shake table investigations confirmed the expectation that input accelerations from the main structure would be amplified at the building services component and that it would not be sufficient to assume that the restraints be designed for a maximum acceleration of 1g. An introduction has been given to the contents of a design guide, which provides both input accelerations that may be used by engineers wishing to design a seismic restraint system from first principles and a selection of acceptable design solutions for satisfaction of the New Zealand Building Code

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