Experimental Program for Determining Leak Rates in Unlined Concrete Shear Walls Subjected to Beyond Design Basis Earthquakes

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ABSTRACT

An experimental program designed to establish leak rates and aerosol penetration for concrete shear walls subjected to beyond design basis earthquakes is outlined. A review of the available literature is provided. The goals of the program, the details of the test specimen, and the testing protocol are presented. The program is funded by the U.S. Department of Energy. The data obtained in this test program are intended for use in safety analysis of nuclear facilities that house small quantities of special nuclear material.

INTRODUCTION

Purpose

This paper outlines an experimental test program designed to provide data on the permeability of normal weight concrete shear walls that have been subjected to lateral forces up to and beyond normal design basis. The need for such a program is clear. There is a large abundance of unlined reinforced concrete shear wall type structures in the U.S. Department of Energy complex. Many of these structures house hazardous materials that may be dispersed through the air during or after an accident. Safety analysts typically make estimates of the leak rate of confined spaces as a function of damage in order to make estimates of off-site consequences. The data available on the permeability of concrete shear wall structures, particularly when these structures are subjected to loads (i.e., large earthquakes) beyond their design basis are limited. More data are needed in order to develop rational design rules for unlined reinforced concrete shear wall that also serve a confinement function.

Background

Reinforced concrete is the material of choice for many of the structures in the U.S. Department of Energy's complex that contain nuclear material. Portions of these structures are designed to function as "tertiary boundaries" in the event of an accident involving the release of radioactive material. For example, in a process facility, geometrically favorable containers may serve as the primary boundary between radioactive material and the environment, gloveboxes which house the containers may serve as the secondary boundary, with the reinforced concrete floor slabs, walls, and roof serving as the tertiary boundary. This defense in depth is part of the Department of Energy's practice in the design of nuclear facilities.

Unlined concrete structures develop shear cracks during earthquake ground shaking. Some of these shear cracks will pass through the thickness of the wall. These through cracks allow airborne contaminants to pass to the exterior of the building, although the cracks may be tight and the path tortuous such that the concrete wall may serve as a "hepa-like" filter. Hence, leak rate evaluation, and the ability of the designer to design to leak rate criteria, is an important issue in estimating the safety of these facilities. Many of the design codes, however, are written to life safety objectives, or to performance objectives that are qualitative at best. There are little data to support the development of design criteria directly related to leak rates.

Scope

The experimental program is designed to provide data on the leak rate of typical reinforced concrete shear walls as a function of damage. The current phase of the program does not include development of design criteria for reinforced concrete shear walls to maintain a set level of leakage. The current program also does not include an examination of the efficiency of products designed to decrease the permeability of concrete walls such as epoxy-based paints, plastic, composite, or metal liners. Follow on studies to this program are planned that will examine these effects.

IMPETUS FOR SHEAR WALL TEST PROGRAM

The use of unlined concrete shear walls as tertiary confinement barriers is commonplace within the U.S. Department of Energy multi-program laboratories. Examples include Los Alamos National Laboratory's Plutonium Facility (TA-55, PF-4), Nuclear Materials Storage Facility (TA-55, PF-41), Chemistry and Metallurgy Research Facility (TA-3, Bldg. SM-29), Weapons Engineering Tritium Facility (TA-16, Bldg. 205), and Casa Buildings (TA-18, Buildings 23, 32, and 116). There are many more examples in the Department of Energy Complex.

DOE-STD-1020 [1] provides design and evaluation criteria for U.S. Department of Energy Facilities. These criteria were written for structural engineers in order to achieve a target risk goal for both nuclear and non-nuclear facilities.

The criteria in DOE-STD-1020 are presented in a graded fashion. The criteria were developed to approximate levels of safety achieved in design that range from those for non-essential facilities, to those for commercial nuclear power plants. The levels of safety (performance goals) are also tied to performance objectives. For the highest level of safety (PC4), the performance objective is defined in DOE-STD-1020 as, "provide occupant safety, provide for continued operation, and provide confidence of hazard confinement." For concrete barriers which serve as tertiary confinement boundaries, the performance objective in DOE-STD-1020 is described qualitatively as, "concrete walls cracked; but small enough to maintain pressure differential with normal HVAC. Don't expect cracks greater than 1/8 inch."

The problem with this definition of performance is that it is not quantitative. The designation and the concept of confinement is easily confused. For most PC4 structures, civil engineering design teams attempt to design the tertiary concrete boundary as a "confinement boundary". Some analysts and reviewing bodies define confinement as leak-tight under nominal pressure. Other analysts will define confinement as maintaining filtration to the same degree of efficiency as HEPA filters.

For the first definition, leak-tight boundary, it has been suggested by design teams and code writing committees [2] that to ensure a leak tight boundary concrete design should follow an allowable stress approach with the stress in the reinforcing being limited to less than yield. The application of this type of design approach would lead to levels of conservatism that are unnecessary. Especially for concrete shear wall structures where the concrete shear walls act as the primary lateral force resisting elements to resist seismic loads. In addition, it is doubtful that an unlined concrete structure would ever be able to provide a leak-tight boundary simply because of the effects of temperature and shrinkage. There are data in the literature that demonstrate reinforced concrete has an intrinsic permeability in the absence of superimposed loads other than temperature and shrinkage due to the curing process.

The second definition, high efficiency particulate filtration, intuitively makes more sense. Most nuclear facilities operate on a design philosophy of filtered confinement. Hazardous materials are confined by physical containers (i.e., geometrically favorable containers, gloveboxes, hot-cells, buildings, etc.), and by filtered ventilation. The air pressure becomes increasingly negative as one travels from atmosphere to a contaminated environment. The flow from the contaminated environment is directed through safety class ducting and HEPA filter banks. Thus, even a highly contaminated room has airflow to the environment, however, it is filtered. The room that surrounds this environment is performing acceptably if it provides filtration to the atmosphere as least as efficient as the HEPA filters in the safety class ducting.

The data in the literature are not sufficient in quantity or quality [3] to derive general design criteria for use in the design and evaluation of unlined concrete shear wall structures, particularly for nuclear facilities where the shear walls also function as tertiary confinement boundaries. The available data are also insufficient to provide a defendable basis for use in safety analyses, which require the calculation of leak rates through concrete confinement barriers. This test program was initiated to derive design parameters for concrete shear walls used as confinement barriers in nuclear facilities. Elements of the program include:

1. A statistical sample (~13) of shear wall test specimens
2. A sample of permeability measurements taken on walls tested beyond ACI Code limits.
3. Parametric studies on the components of reinforced concrete in order to investigate the effect of concrete strength, reinforcement ratios, and normal stress on the permeability of unlined walls.

Subsequent phases of the test program will investigate the effect of adhesive coatings applied to the face of unlined structures in order to increase the particulate filter efficiency, and will develop design rules tied to the desired permeability for unlined concrete shear wall type structures.

This test program is a multi-year effort conducted by Los Alamos National Laboratory in collaboration with the University of California at Irvine Department of Civil and Environmental Engineering.

LITERATURE REVIEW

The flow rate of air through concrete depends upon the air permeability, the thickness of the concrete, and the pressure gradient applied. The air permeability coefficient is dependent upon the concrete mix parameters, mixing and compaction methods, curing conditions, and age. Typically, factors that improve the compressive strength of the concrete will decrease its permeability. Permeability increases with increasing water/cement (w/c) ratio. Curing reduces air permeability, but drying significantly increases permeability at any age. Although a specific concrete may be permeable to air, it may be impermeable to some other gases. Cracks and joints provide additional paths for air leakage. Air leakage rate through cracks is a function of the number of cracks, spacing, width, and penetration depth into the concrete. The flow rate may be computed based on uncracked concrete properties for cracks that do not completely penetrate the wall.

The flow rate appears to be inversely proportional to the slab thickness and directly proportional to the pressure difference across the slab. Tests with pressure gradients up to 7.6 kPa (1.1 psi) on concrete with thickness varying from 10.2 cm (4 in) to 22.9 cm (9 in) resulted in leak rates in cubic centimeters per square meter per hour equal to approximately 162 times the ratio of pressure (kPa) to thickness (cm) [4]. These flow rates correspond to an air permeability coefficient through undamaged concrete of 4.22×10^{-12} m^4/kg-s (4.6×10^{-6} in^4/lb-s). This value for the permeability coefficient is typical for concrete with 27.6 MPa (4000 psi) compressive strength at 28 days made with 1.9 cm (¾ in) maximum size aggregate, 227 kg (500 lb) cement per 0.74 m^3 (cubic yard), and a w/c ratio of 0.50.

A literature review covering the past 30 years examined published works on air permeability measurements in concrete. Most of the works reviewed dealt with gas flow and permeability measurements in undamaged concrete. In 1973, Figg published a method for the in-situ determination of the air permeability of concrete [5]. The concept is based on:

1) drilling a hole into the surface of the concrete,
2) sealing the top of the hole with a silicon rubber plug,
3) inserting a hypodermic needle through the plug,
4) drawing a vacuum in the hole, and
5) correlating any pressure increase in the hole with the air permeability in the concrete surrounding the hold.

Despite being limited to a maximum of 1 bar (14.5 psi) in pressure differential, researchers found this method useful. Cather et al. [6] and Kasai et al. [7] modified the method for increased practicality. The 1 bar (14.5 psi) pressure limitation was overcome by Hansen et al. [8] who developed an apparatus that applies low air pressure to the surface and monitors the pressure increase over time in a hole drilled to a known depth under the pressurizing apparatus. All in-situ procedures reviewed made air permeability measurements within 5 cm (2 in) from the surface.

Several in-situ and laboratory experiments were aimed at correlating air permeability with concrete characteristics. Kasai and coworkers [9] used their version of the in-situ vacuum test apparatus to determine a relationship between air permeability and concrete carbonation. In addition, they determined that the air permeabilities of concrete with w/c ratios of 45% and 55% have about ¼ the air permeability of concrete with a 65% w/c ratio. Laboratory experiments on concrete specimens of various dimensions were also used to characterize air permeability. Nagataki and Ujike [10] investigated the behavior of airflow through concrete containing fly ash and condensed silica. They found that the air tightness of concrete is improved with the addition of fly ash and silica fume because of these constituents effect on porosity. Martialay [11] investigated the change in air permeability of concrete slabs over a 20-year period and found that it stabilized in that period. Schonline and Hilsdorf [12] confirmed the behavior of air permeability, which has been summarized previously, relative to curing, w/c ratio, and fly ash content. Laboratory tests to measure the intrinsic permeability of concrete were developed by Dhir et. al. [13]. As a result of this work, the air permeability test was found to provide a direct measure of the intrinsic permeability of concrete and results from the air test could be used to characterize hydraulic permeability.

A few research articles on airflow through penetrations and liner materials were also examined. The influence of air leakage through concrete is slight when compared with air leakage through construction joints. Tests were performed by Nojiri and Fujii [14] to investigate the air tightness of concrete with and without construction joints. Minimizing the air leakage through construction joints and penetrations was identified as a controlling efficiency factor if concrete was used for evaporator shells. The gas permeability characteristics of organic polymeric materials, suitable for use as liners in concrete containment structures, were studied experimentally by Epstein and coworkers [15]. The permeation of air, nitrogen, oxygen, krypton, and xenon was measured in polyvinyl chloride and chlorosulphonated polyethylene. This study concluded that, by using plastic liners, fission gas leak rates can be expected in the range of a few hundredths of a percent of the total contained volume per day.

Rizkalla et al. [16] proposed a mathematical expression for the rate of pressurized air flow through idealized cracks. In their work, Rizkalla et al. simulated the membrane stresses in a concrete containment structure subjected to large internal pressures by tensioning the longitudinal reinforcement which protrude along the ends of the test specimen. Steady-state differential air pressures were created by controlling the pressurized air to the upstream chamber of the specimen, while maintaining the downstream pressure at atmospheric pressure. Rizkalla refined the proposed equation for flow rate by using the experimental data obtained from several concrete specimens subjected to uniform tensile stresses. Although these data are valuable, it is doubtful whether these data are applicable to seismic induced shear cracks, or out-of-plane bending cracks.

Mayrhofer et al.[17] investigated the airflow through cracked reinforced concrete. This effort aimed at determining the gas impermeability of shelter roof slabs loaded to their maximum carrying capacity with uniform pressure. The out-of-plane pressure load causes the slabs to bend. Gas impermeability for the slabs was defined by the ability to maintain a minimum overpressure of 0.5 to 1.0 mb. Square slabs with length dimensions of 114 cm (45 in) and 300 cm (118 in), 0.14% and 0.3% reinforcement by area, and a thickness of 17.8 cm (7 in) were used in the experiments. The slabs were pressure loaded statically in monotonically increasing load steps. Airflow was measured upon completely unloading the structure after each load step. Data presented included static load-deformation curves, crack patterns, and airflow-overpressure curves. A mathematical expression to correlate slab deflection with gas permeability was described in detail. A correlation between deformation and permeability was possible because the loading and resulting crack patterns in all slabs were similar.

Girrens and Farrar conducted an experiment in the early 1990’s to quantify the leak rates of a specific configuration of unlined concrete shear walls subjected to seismic excitation [18, 19] up to the level specified for design. The geometry of the test specimen was based on a load bearing shear-wall for the Special Nuclear Materials Laboratory (SNML). The specimen was subjected to quasi-static loads simulating earthquake demand for in-plane shear. The specimen was loaded for 3 cycles each to nominal base shear stress levels of ± 414 kPa (60 psi), ± 896 kPa (130 psi), and ± 1310 kPa (190 psi). These stress levels correspond to approximately 12%, 26%, and 38% of code specified capacity (V_u). Where V_u is computed in accordance with ACI 318-95 [20] for the test specimen as:

$$V_u = \Phi V_N = \Phi\left[A_{CV}\left(\alpha_c\sqrt{f_c'}\right)+\rho_n f_y\right] \qquad \text{[20, eqn. 21.7]}$$

where Φ is 0.85, and the coefficient α_c varies linearly from 3.0 for (h_w/l_w)=1.5 to 2.0 for (h_w/l_w)=2.0. The test specimen has a h_w/l_w ratio of ¾; thus, α=3. The test specimen had a 95% exceedance concrete strength value (f'_c) of 39.8 MPa (5772 psi), specified minimum steel yield strength of 414 MPa (60,000 psi), a horizontal steel reinforcement ratio of 0.0061, and an area of concrete effective in resisting shear force of 1858 cm^2 (289 in^2). Thus,

$$V_u = 6.36x10^5 \text{ N (145 kips),}$$

where f'_c is taken as the 95% exceedance strength value from test data, as opposed to the specified minimum value of 27.6 MPa (4000 psi).

Permeability measurements were made on the wall both before and after the cyclic loading. A final single load cycle test of ± 1965 kPa (285 psi) (57% of V_u) was performed. The results indicated that there was no change in the intrinsic air permeability of unlined concrete shear walls provided the linear load-displacement response limit is not exceeded. The results also showed that the intrinsic air permeability increased by a factor of 40 after the onset of through wall shear cracks. The shear cracks occurred in the test to 1965 kPa (285 psi). The onset of shear cracks was predicted to occur at an equivalent shear stress of 1586 kPa (230 psi). These data suggest that for design of unlined concrete shear-wall type structures, the code capacity equation in ACI 318-95 should be modified to account for the concrete contribution to overall shear strength, and discount the steel contribution:

$$V_u = \Phi V_N = \Phi A_{CV}\left(\alpha_c\sqrt{f_c'}\right)$$

A follow on experiment was performed on the cracked shear wall by Farrar et al [19]. Aerosol penetration measurements were conducted on the cracked shear wall structure. The sample collection airflow was maintained at 1.5 cm^3/s (0.092 in^3/s), with an average pressure gradient of 2.8 kPa (0.4 psi). A 0.10-µm monodisperse PSL aerosol was injected into the steady airflow. The aerosol penetration through the cracked shear wall was 0.5%. The corresponding filter efficiency was 99.5 %.

Suzuki et al investigated the gas leakage rate through cracks in both reinforced and unreinforced concrete [21]. Sensitivity studies on the leakage rate due to the kind of fine aggregate and the size of the course aggregate were performed. Suzuki’s test were limited to concrete crack widths less than 0.5 mm (≅1/50 in), and differential pressures less than 250 kPa (36.2 psi). Although limited in samples for reinforced concrete, Suzuki’s recommended flow equations based on his empirical data may be used as a benchmark.

Okamoto and others performed an experiment on a three-dimensional one-tenth-scale specimen based on a part of a prototype boiling-water reactor nuclear power plant [22]. The study was conducted to measure the air-leakage as a function of lateral load, or shear cracks. The specimen was subjected to nine static load cycles up to and beyond the specimen design bases. Leakage rate data were obtained at both the peak, and upon removal of the load at each cycle.

Greiner and Ramm [23] performed a series of experiments on both reinforced concrete and unreinforced concrete in an effort to derive an equation for the leak rates of air as a function of crack width and overpressure. Their efforts were limited to the following parameter ranges:

1.	crack width,	$0.20 \text{ mm} \leq W \leq 1.30 \text{ mm}$	$(0.008 \text{ in} \leq W \leq 0.05 \text{ in})$
2.	overpressure at the beginning of the crack,	$0.10 \text{ MPa} \leq \Delta P \leq 0.80 \text{ MPa}$;	$(14.5 \text{ psi} \leq \Delta P \leq 116 \text{ psi})$
3.	grading curves,	AB 8, AB 16, AB 32.	

They concluded that for unreinforced concrete, their proposed flow equations were good for the experimentally proven ranges, while for reinforced concrete, their predicted flow equations were conservative (i.e., measured flows were less than those predicted).

Dameron et al [24] evaluated leak test results that were available in the open literature, and suggested a methodology for calculation of leak rates in lined concrete containment vessels. As part of their research, Dameron et al, were required to estimate the flow rate through the concrete containment vessel. They used the method developed by Rizkalla [16] in calculating the measured leak rates, and found good agreement between the measured values and the calculated values for microconcrete. They noted, however, that Rizkalla's roughness coefficient, k, needed to be multiplied by a factor of 1000 to get good correlation between the predicted flow rates and the measured flow rates in the test specimens that used full-scale concrete and aggregate.

Riva et al performed a single experiment on a reinforced concrete slab subjected to differential pressure and uniaxial tension. In their experiment, they compared the measured leak rates with those calculated using the leak formulae available in the literature [25]. Riva concluded that, among the formulations considered:

1) the leak rate prediction formula given by Rizkalla et al. [16] provides the best fit to his experimental data,
2) the leak rate prediction formula given by Greiner and Ramm [23] would be more suitable for higher differential pressures (> 0.1MPa) (14.5 psi);
3) the Poiseuille equation generally overestimates the leak rate, and
4) the expressions by Suzuki et al. [21] obtained the best results for the smallest pressure gradient (0.01 MPa) (14.5 psi).

In summary, the literature review indicates that there are very little data on the permeability of cracked reinforced concrete or on earthquake damaged reinforced concrete. Data that are available include that published on gas permeability in undamaged concrete, that published by various researches on concrete subjected to uniaxial tension, and that of Farrar and Girrens on the single shear wall tested to below its design capacity. The experimental data available on cracked concrete were directly applicable for reinforced concrete containments that are subjected to high internal pressure loads. This loading condition would lead to a state of stress that could be approximated by uniform tension. These data are not directly applicable for the US. DOE needs because of the test specimen size and the loading configurations.

TECHNICAL APPROACH

The technical approach to be used is identical to that previously used by Girrens and Farrar [18, 19], with some minor modifications. There is a high degree of confidence in the success of this experiment since this approach has already been used. Details of the experimental set-up, test procedure, loading sequence, and leak-rate measurements are discussed in this section.

The experimental approach consists of the following steps:

1) Construct model specimens in the laboratory
2) Perform in-situ permeability (leak rate) and particulate filtering efficiency tests on structures before shaking.
3) Displace structures to ASCE-XXX [26] limit states A, B, C, and D for shear controlled concrete shear walls.
4) Perform in-situ permeability and particulate filtering efficiency test on structures after removal of load or deformation.

Data obtained from the experiments will allow a defendable basis for defining deformation limits used in the design of nuclear facilities. Furthermore, the data will allow a more realistic basis for calculating leak rates as a function of seismic damage state in these types of facilities.

For the direct measurement of the permeability of concrete in accordance with Darcy's law, conditions of steady state should exist. The volume flow rate is proportional to the area, the pressure gradient, and the intrinsic permeability, which is independent of the properties of the migrating fluid. The volume flow rate, Q, may be expressed by the following:

$$Q = \frac{-kA}{\mu}\left(\frac{dp}{dl}\right) \qquad [18, \text{eqn. } 1]$$

The permeability coefficient for a specimen of uniform thickness L, with the downstream face at atmospheric pressure, under steady state flow may be estimated by the following:

$$k = \frac{2\mu L\overline{P}\,\overline{Q}}{A}\left(\overline{P}^{2} - P_{ATM}^{2}\right)^{-1} \qquad [18, \text{eqn. } 3]$$

Where:

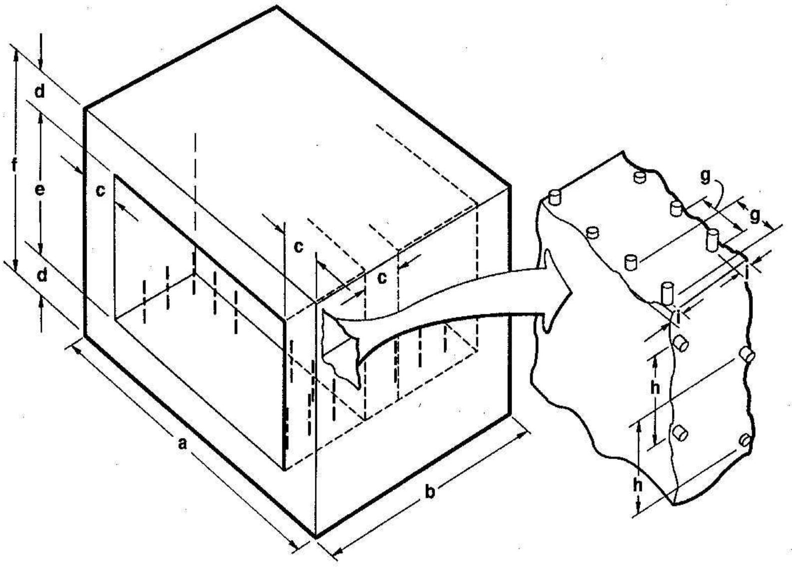
μ = dynamic viscosity of gas (Pa/s),
L = wall thickness (m)
$\overline{P}$ = average pressure between successive samples at times t, and t+Δt (Pa)
$\overline{Q}$ = average volumetric flow rate between successive samples (m^3/s)
A = wall area normal to the flow (m^2),
P_{ATM}= atmospheric pressure (Pa), and
Δt = measured time increment (s),
Q = volume flow rate (m^3/s),
k = intrinsic permeability (m^2)

Experimental Test Set-up and Procedure

For the initial test case, a single reinforced concrete shear wall specimen will be fabricated to the exterior dimensions shown in Figure 1. This specimen was selected as representative of typical concrete bearing walls used in the DOE complex.

Two rows of reinforcing will be used throughout the model. These layers are to provide reinforcement ratios in both the horizontal and vertical dimensions which are typical for a load bearing concrete shear wall. A steel bearing plate attached to a wide flange beam will be attached to the top of the test specimen so that both horizontal and vertical loads may be applied to the specimen. The test set-up, showing the load cells and load device is shown in Figure 2.

The test specimen has a volume of approximately 0.21m^3 (7.4 ft^3) on either side of the shear wall. The concrete mix will have 1.9 cm (0.75 in) maximum size aggregate with a 27.6 MPa (4000 psi) minimum 28-day compressive strength. Ten standard test cylinders will be taken during the concrete placement for each specimen per ASTM C172-82 and C31-84. The cylinders will be tested for modulus of elasticity (ASTM C469-83) and ultimate compressive strength (ASTM C39-84).



	DIMENSIONS (in.)									REBAR	MAX AGGREGATE
STRUCTURE	a	b	c	d	e	f	g	h	i	diam	SIZE
MODEL 1	48	36	6	6	24	36	3	6	1	0.375	0.75

Figure 1
Specimen Overall Dimensions

LOADING SEQUENCE

A load frame will be constructed to support the test structure, a hydraulic actuator used to apply a lateral load to the structure, and two hydraulic jacks used to apply a constant vertical load to the structure. The general load structure as applied to a test specimen is shown as a schematic in Figure 2.

The load sequence will follow a modified version of the ATC-24 protocol [27]. The first load increment will be performed using force based protocol, and will be terminated at a code specified strength limit. The shear strength equation prescribed by a revision to DOE-STD-1020 [1] will be used to define the nominal shear strength limit:

$$V_N = 0.69\sqrt{f_c^`} - 0.28\sqrt{f_c^`}\left(\frac{h}{l} - 0.5\right) + \frac{N_A}{4lt_n} + \rho_{se}F_Y$$

Where:

$f_c^`$ = concrete strength (MPa)

h = height of the wall (m)

l = length of the wall (m)

t_n = thickness of the wall (m)

N_A = normal force (MN)

F_Y = yield strength (MPa)

ρ_{se} = effective reinforcement ratio [1]

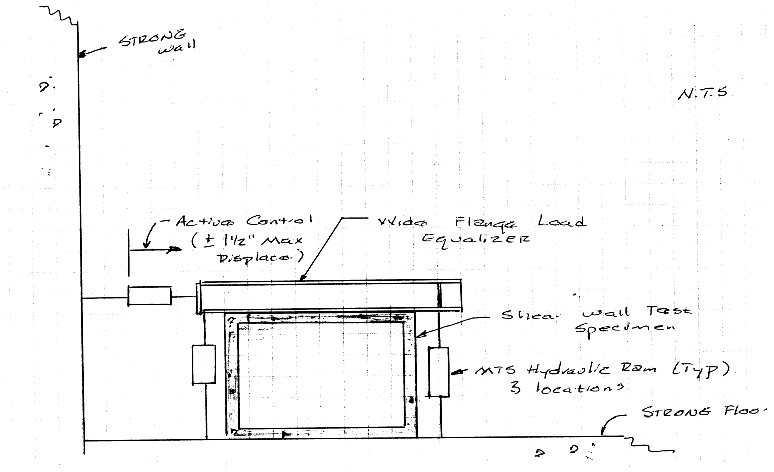


Figure 2
Typical Shear Wall Test Structure and Load Cells1

Additional load sequences will be follow a displacement protocol. The subsequent load cycles will correspond to drift limits of 0.2%, 0.4%, 0.6%, and 0.75%.

LEAK RATE MEASUREMENTS

Leak rate (air permeability) and aerosol penetration measurements under steady state flow conditions will be made on the test structures before and after loading. The leak rates will be performed at differential pressures between 0.1 bar (0.2 psi) and 0.14 bar (2.0 psi). Before loading the structures, an airtight coating (epoxy paint, rubber liner) will be applied to the side of the shear wall to be pressurized. Cover plates will be attached with 1.27 cm (0.5 in) threaded rods to each open end of the test structure, as shown in Figure 3. The cover plates will provide resistance and sealing support for internal pressurization. Internal pressurization of the test structure shall not exceed 0.14 bar (2.0 psig). Volumetric airflow through the shear wall will be monitored with a laminar flow element system.

AEROSOL PENETRATION MEASUREMENTS

Aerosol penetration will be measured under steady state flow conditions through the shear wall at various differential pressures. A second cover plate will be installed to enclose the downstream ambient pressure side of the test structure, permitting the measurement of the accumulation of non-test particles for a background particle distribution. Throughout the penetration tests, the ambient pressure measured inside the downstream volume shall be kept constant by means of a pressure control vacuum. At steady state conditions, a bidisperse aerosol (0.20 μm) of di (2-ethylhexyl) (DOP) particles is to be injected in the upstream side of the wall and will be allowed to equilibrate in the pressurized volume before sampling. Samples will be extracted through a penetration in the cover plate, then run through a laser aerosol spectrometer (LAS) to measure the aerosol challenge to the shear wall. Samples will also be extracted from the downstream side of the wall, then analyzed with the LAS to measure the penetration particle distribution.

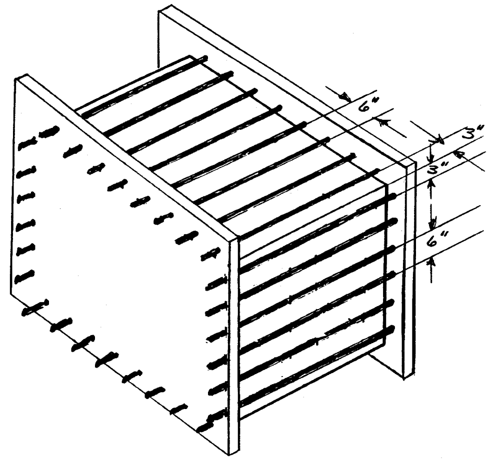


Figure 3
Shear Wall Test Structure With Cover Plates

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