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Structural Engineering and Applied Mechanics

Dynamic Properties of Fire Sprinkler Systems

By
JAMES S. DILLINGHAM and RAKESH K. GOEL

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DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINEERING
CALIFORNIA POLYTECHNIC STATE UNIVERSITY
SAN LUIS OBISPO, CA 93407

ABSTRACT

Four fire protection systems have been attached to a small building model for testing their dynamic properties. Three of the systems used CPVC (fire rated) plastic pipes while the fourth was made from schedule-40 steel pipe. The building model was securely attached to a three by three foot shake table in one of two orientations and was able to experience base accelerations along both its principle axis (longitudinal, transverse). Test procedures involved sending a sine sweep with a progressively increasing frequency at a constant acceleration value. Various recording locations provided data showing fundamental frequencies with pronounced amplification over the base input accelerations. First the buildings natural frequencies were obtained. Then each sprinkler system was tested for acceleration values at the sprinkler drops. Sprinkler drops were affixed with an accelerometer at the fitting connection and one at the sprinkler head. Comparisons are made between the fundamental frequencies of the building and the fire sprinkler system.

An analytical model of the four sprinkler systems was designed on the SAP2000 computer program. The test frequency range providing clean data was from 10 Hz – 25 Hz. In this range the computer analysis identified all of the first observed fundamental frequencies. The SAP2000 Analysis also identified the distinct second fundamental frequencies obtained from testing.

Large acceleration amplifications were observed at fundamental frequencies in the building and in the sprinkler systems. The largest amplification was sixty times that of the base input experienced by one of the CPVC drops. The steel sprinkler line also experienced large amplification values of up to 35 times the base level acceleration. The fire systems were filled with water to simulate a wet-system and to indicate potential failures. No failures occurred in any of the four test systems. After testing each sprinkler design multiple times it is concluded that sprinkler systems should remain functional following a seismic event. Sprinkler systems installed to NFPA-13 code (National Fire Protection codebook) standards have been proven to perform in earthquakes as well as the structures they’re attached to. Improper connectors and lack of required pipe clearances are the main factors attributed to researched fire system failures.

ACKNOWLEDGMENTS

Testing was facilitated through the generous assistance from the following two contractors: Wayco Fire Protection Inc., 763 Alphonso Street, San Luis Obispo, CA; and Alpha Fire Protection Corp., 650 Sweeney Lane, San Luis Obispo, CA. Only fire protection contractors are able to order fire sprinkler materials. Creating fire sprinkler tests designs would not have happened without their material donations. Special thanks to Kevin Hooper of Alpha Fire Protection for providing research materials. Special thanks to Bob Rose of Wayco Fire Protection. Bob provided all the sprinkler material used for this report free of charge.

This report is same, except for some editorial changes, as Jim Dillingham’s master’s thesis submitted to the California Polytechnic State University at San Luis Obispo. The thesis committee consisted of Professors Rakesh K. Goel (Chairman), Eric Kasper, and H. Mallareddy. The authors are thankful to Professors Kasper and Mallareddy for reviewing the thesis manuscript.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF GRAPHS

1 INTRODUCTION

LITERATURE REVIEW

The Fire Sprinkler Advisory Board of Southern California published Northridge Earthquake January 17,1994, a report that compiles efforts of the National Fire Sprinkler Association with the U.A Sprinkler Fitters Union to identify automated sprinkler line failures in the San Fernando Valley resulting from the Northridge Earthquake. The report findings suggest that failed sprinkler systems were either result of a failed structural system or from use of construction practices non-compliant with current codebook NFPA-13. Modern sprinkler systems performance to a large seismic event proved to be resistant to failure, documented in the findings from the Northridge Quake.

NFPA-13 outlines code requirements for fire sprinklers installation used throughout the United States. American Building code refers to NFPA-13 and requires modern designs to conform to the specified procedure. The preliminary investigation to this study involved review of the NAPA-13 codebook. Special attention was paid towards the seismic and static support sections. The sprinkler designs used in the experimental test of this report conformed to all NFPA-13 requirements. Because the small size of the sprinkler designs tested, support and seismic bracing used were conservative according to NFPA-13 requirements.

PURPOSE OF RESEARCH

Failure means the discharge of the system due to breaking of service pipes. Broken sprinkler systems will release water until the shut-off can be reached. Frequently large financial losses result from interior water damage after fire-system failure. When a sprinkler system discharges due to fire discharge, only the areas burning hot enough will melt the glass bulbs and discharge the sprinklers. The mechanical properties of the sprinkler head allow for near a hundred percent reliability. Failure of fire sprinklers almost always results from shearing pipe or pulling out from compression fittings. Because a fire sprinkler system failure carries with it large consequences, the decision was made to study the seismic reaction to sprinkler designs.

Fire sprinkler design changes on a continual basis as new and improved design components become available. Enough design change has occurred within the past ten years that anyone with limited knowledge of the system could detect the age of the technology. If a fire protection system is properly designed to NFPA-13 standards the system should suffer no damage other than that imposed by a failing structure. Prior to 1990 California allowed plumbers to install fire protection. Now in California only licensed fire protection contractors are allowed to install sprinkler systems. California's efforts to establish design conformity have provided for current and upgraded designs to perform under seismic loads. Most failures of sprinkler systems within undamaged structures are a result of systems with old static designs or even more commonly of poor workmanship. Without proper enforcement by planning officials the codes in place are always vulnerable to being overlooked.

During the January 17, 1994 Northridge Earthquake, most of the 3000 + sprinkler systems failed only when the surrounding structural components failed. However some structures sustained sprinkler failure with no other associated building failures. These cases were mostly due to improper or outdated installation procedure. Northridge Hospital and St. John's Hospital in Santa Monica both experienced failed sprinkler systems without any structural collapse. Both sprinkler designs were insufficient by current code standards. The two most common code infractions, pullout of powder driven studs and insufficient clearance given to pipes passing through membranes, caused failures at the Northridge Hospital. At the St. John's Hospital sprinkler failure resulted from insufficient seismic bracing, the contractor performing the repairs reported the system having no retaining straps. Both hospitals lost beds during a critical crisis event in the city (FSAB, 1994, Appendix C).

The beginning conception entailed utilizing resources available at Cal Poly State University as well as from local sprinkler contractors to create a legitimate model for testing. Projected outcome included recordings of several induced accelerations as well as witnessing a potential failure.

OBJECTIVES

After deciding to study the dynamic properties of fire sprinklers the desired testing procedure developed. The goals of experimental testing were as follows:

- To use the available seismic testing equipment available at the Dynamics Lab, Building 13, Cal Poly State University, San Luis Obispo, California.
- Develop a model capable of containing a fire sprinkler system and adapted to fit on the Shake Table in the Dynamics Lab.
- Obtain data representing fire protection systems undergoing induced seismic forces.

REPORT REVIEW

Results from this study are obtained through frequency sweep tests preformed on both the test model and the particular sprinkler system plumbed within. For each test a frequency sweep was pasted through the model at a specified transmitted input acceleration. The symmetry of the bolt pattern on the test table allowed for the model to be tested in the two main perpendicular axes. The Shake table shakes in one direction and the model was rotated to align the desired side of the model to the shake direction. For testing the long side of the model is labeled Longitudinal and the short side is labeled the transverse side. The first and second natural frequencies of the model were observed prior to installing sprinklers.

2 REVIEW OF SEISMIC CODES

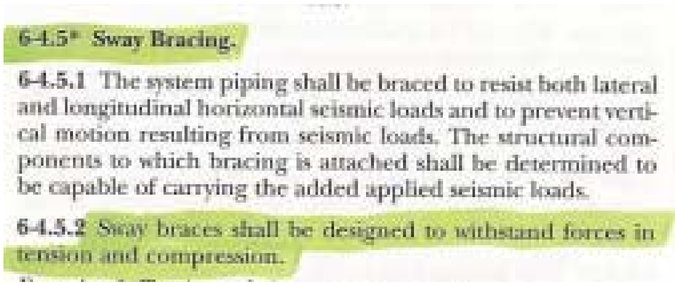
In the seismically active Western United States building codes have been adopted to provide for adequate resistance to horizontal ground accelerations from structures as well as to their mechanical elements. The State of California adopted the U.B.C. as a minimum building standard in 1991. At the same time California adopted the 1989 edition of NFPA-13, as standard for sprinkler system design. Separate editions NFPA-13R and NFPA-13D outline sprinkler design for residential units up to four stories and single-family dwellings or mobile homes respectfully. NFPA-13 currently outlines the national standard fire sprinkler installation. Both codes state: the structure must be designed for it's intended loads and be able to tolerate expected ground movements. A fire protection system designed in California must follow NFPA-13 standards to insure the system can remain intact while the building shakes from ground accelerations

Expected possible earthquake responses are taken from the historical record. Occasionally that database might grow, for example, when a previously unrecorded faults slips. County planning departments assign a seismic Roman numeral classification within their governing territories based on available earthquake records. Direct zones of influence from active faults in the region are the best indications for assuming probable ground accelerations. Counties give special seismic consideration to design in regions of high earthquake probability and in structures considered vital for community well being. Along with design of structural components, special design considerations need to be made for the mechanical and electrical components. In an attempt to maintain serviceability of structures during severe ground movement both the U.B.C. and NFPA-13 outline seismic design requirements necessary to stabilize the structure and prevent possible failures within. The section on fire sprinkler seismic design, NFPA-13-6 is included in the appendix.

The automatic fire sprinkler code, NFPA-13, covers system design from where the supply line contacts the foundation and on into the structure. When subsurface pipe failures occur from ground movement they are often the result of concrete pieces penetrating the ductile iron pipe within the surrounding trench backfill. Often shut-off valves are installed in-line along the exterior riser before the supply line enters the building. Some counties will require in-line monitoring units such as activation alarms and pressure gauges to be installed in the supply line. In seismic zones special flexible couplings must be installed to allow for any variability in ground and building motions during ground accelerations.

When the main line rises from the sub-surface to the building the pipe must be connected using OSHPD pre-approved flexible fittings and, as with all vertical risers, secured at the top by a proper four-way sway brace. Flexible fittings (bends, tees and couplings) are utilized throughout sprinkler designs as required by NFPA-13. Flexibility is achieved by clamping a rubber seal around grooved ends. Attention must be paid to worn seals in order to prevent potential failures. The code requires flexibility connection joints through out sprinkler systems as well as seismic bracing on pipes to insure the sprinkler system will move only with the building. The code also makes provisions for proper clearance required for pipes penetrating solid membranes.

Proper seismic bracing is critical for a designs seismic performance. A high percentage of recorded sprinkler system failures resulting from the 94' Northridge Earthquake was caused from the improper installation of the seismic bracing. Seismic bracing consists of steel connection members used as tension members, compression members, or commonly both. The NFPA-13 codebook requires the seismic braces are used to resist any potential movement of the sprinkler pipes. The codebook refers to seismic braces as sway braces.



6-4.5* Sway Bracing.

6-4.5.1 The system piping shall be braced to resist both lateral and longitudinal horizontal seismic loads and to prevent vertical motion resulting from seismic loads. The structural components to which bracing is attached shall be determined to be capable of carrying the added applied seismic loads.

6-4.5.2 Sway braces shall be designed to withstand forces in tension and compression.

Figure 1 NFPA-13-6-4.5 Sway Bracing

The two most common reasons for failure of seismic restraints are when the restraint member pulls away from its support attachment and when the restraint member shears at a threaded connection. Both cases are usually related to improper construction procedures.

Connection bolts have been known to pull out from structural members if they had been fastened using short-cut methods. Contractors have been known to use powder-shot fasteners in the form of penetrating hardened steel nails. These are shot from a gun using a .22 caliber charge; they quickly fasten locations to concrete or steel. The shot-driven anchors are unsuitable for overhead installations due to their low pullout value. Many of the sprinkler line failures reported during the Northridge earthquake were due to powder-shot fastener pulling out from both steel and concrete surfaces.

Proper anchorage for seismic bracing on the structural elements is:

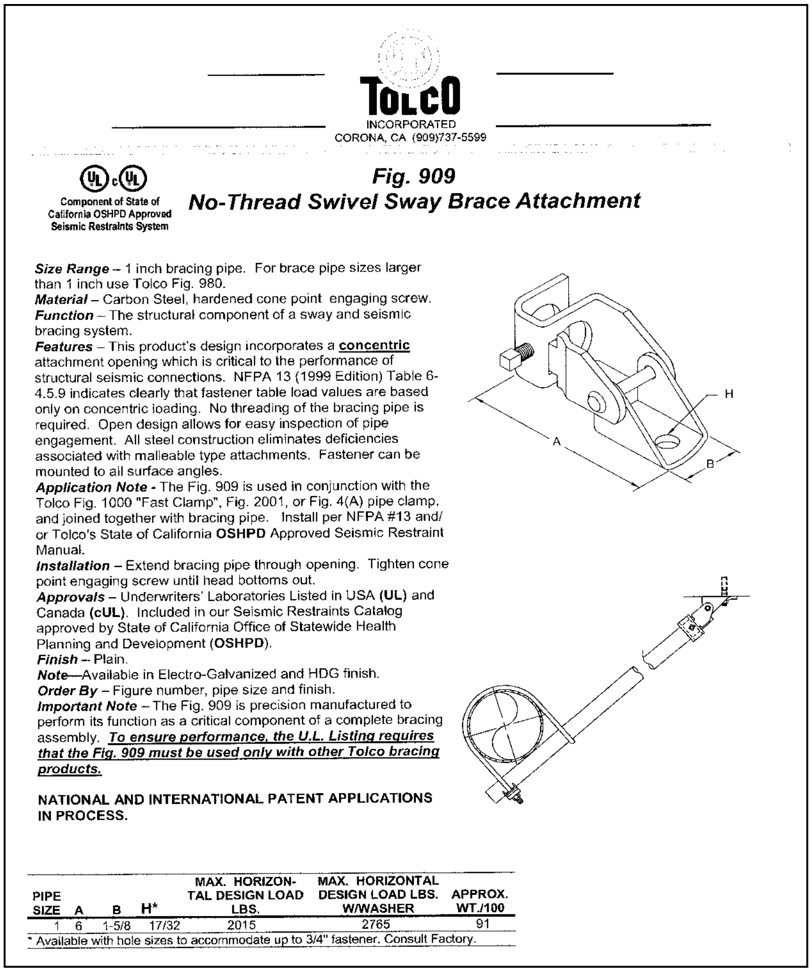
For Concrete, wedge anchor bolts or cast in place anchor bolts:

For Steel, through bolts at approved locations or welded connections;

For Wood Parallel to Grain, through bolts or for thick members lag screws pre-drilled to 1/8 less than screw shank, (NFPA-13 4-14.4.3.5.6). Seismic bracing has commonly dislodged from wood supports when lag dolts were hammered into pre-drilled holes for fasteners (evidently was once a common trade practice in areas).

The code does not require lateral seismic bracing when the pipe support is less than six inches. No seismic bracing is usually needed for CPVC sprinkler designs other than that which is provided by the support anchors them selves. The CPVC supports hold the pipe close to structure providing both lateral and horizontal support. Steel sprinkler designs are usually supported from the structure at a distance greater than the six inches. The following two figures are a picture of the seismic brace used in the steel sprinkler system testing and a company description of the product.

Figure 2 View of the Seismic Brace used in the Steel Sprinkler Design



TOLCO
INCORPORATED
CORONA, CA (909)737-5599

Component of State of California OSHPD Approved Seismic Restraints System

Fig. 909
No-Thread Swivel Sway Brace Attachment

Size Range – 1 inch bracing pipe. For brace pipe sizes larger than 1 inch use Tolco Fig. 980.
Material – Carbon Steel, hardened cone point engaging screw.
Function – The structural component of a sway and seismic bracing system.
Features – This product's design incorporates a **concentric** attachment opening which is critical to the performance of structural seismic connections. NFPA 13 (1999 Edition) Table 6-4.5.9 indicates clearly that fastener table load values are based only on concentric loading. No threading of the bracing pipe is required. Open design allows for easy inspection of pipe engagement. All steel construction eliminates deficiencies associated with malleable type attachments. Fastener can be mounted to all surface angles.
Application Note - The Fig. 909 is used in conjunction with the Tolco Fig. 1000 "Fast Clamp", Fig. 2001, or Fig. 4(A) pipe clamp, and joined together with bracing pipe. Install per NFPA #13 and/or Tolco's State of California **OSHPD** Approved Seismic Restraint Manual.
Installation – Extend bracing pipe through opening. Tighten cone point engaging screw until head bottoms out.
Approvals – Underwriters' Laboratories Listed in USA **(UL)** and Canada **(cUL)**. Included in our Seismic Restraints Catalog approved by State of California Office of Statewide Health Planning and Development (**OSHPD**).
Finish – Plain.
Note—Available in Electro-Galvanized and HDG finish.
Order By – Figure number, pipe size and finish.
Important Note – The Fig. 909 is precision manufactured to perform its function as a critical component of a complete bracing assembly. ***To ensure performance, the U.L. Listing requires that the Fig. 909 must be used only with other Tolco bracing products.***

NATIONAL AND INTERNATIONAL PATENT APPLICATIONS IN PROCESS.

PIPE SIZE	A	B	H*	MAX. HORIZONTAL DESIGN LOAD LBS.	MAX. HORIZONTAL DESIGN LOAD LBS. W/WASHER	APPROX. WT./100
1	6	1-5/8	17/32	2015	2765	91

* Available with hole sizes to accommodate up to 3/4" fastener. Consult Factory.

Figure 3 No-Thread Swivel Sway Brace used for Steel Design

A common cause of brace failures befalls when thin walled threaded pipes are improperly used in a cross-member, shearing can occur at their weak threads. Sprinkler system failure can also stem from improper clearance between pipes passing through floors and walls. When a building shifts from ground acceleration those passageways without proper clearance bind and shear confined pipes within. The NFPA-13 code requires an extra 2 in diameter clearance for pipes less than 4 inches in diameter and an extra 4-in diameter clearance for pipes with 4 inches or greater diameter, (NFPA-13 sec 4-14.4.3.4.1). Almost never will a sprinkler system fail at the sprinkler heads during an earthquake.

Seismic Design according to NFPA-13

- Make sure lengths crossing structural separations are fitted with flexible fittings to protect against differential movement.
- Provide the required pipe clearances through any penetrated membrane. Keep sprinkler system at least 2 inches away from any structural member.
- After the required pipe sizes have been chosen, seismic bracing is required where the support hangers have a drop length greater than 6 inches.
- Install lateral braces at a maximum spacing of 40ft on center and at the end of any feed or cross main.
- Install longitudinal bracing with a maximum spacing of 80ft on center and no greater than 40 ft from the end of a pipe.
- Determine the brace size from NFPA-13 Table 6-4.5.8 based on brace angle.
- Braces must be attached to structural members using the appropriate fasteners outlined in NFPA-13 Table 6-4.5.9.

3 TYPICAL SPRINKLER SYSTEMS

Three types of piping materials are available for sprinkler installation. The traditional steel pipes are still the most common, especially in commercial settings. The use of copper and high-pressure CPVC Pipe has been gaining popularity in the light commercial and residential markets. The limits on copper and CPVC piping diameters still make them suitable for most residential and light commercial applications. CPVC's fire rating makes it unsuitable for most commercial applications.

COMMERCIAL DESIGN

Large steel supply and distribution pipes are joined using compression fittings. For 2 1/2in or larger diameter piping, NFPA-13 outlines seismic standards for required flexure joints, (NFPA-13 4-14.4.3.2). These standards require flexibility within the system design with a purpose to prevent possible shearing of the sprinkler line. Large steel supply lines must be supported for static loads as well as being braced for seismic loads. The codebook provides required guidelines that designers must follow. Designers must choose their pipe sizes according to the quantity of water required for the cubic feet of service area. As with all the mechanical systems within a building, the goal for the design in seismically active regions is to limit the potential for shearing by providing flexibility and to decrease potential moment forces by properly fixing flexible sections. Providing the most optimum system would entail obtaining the highest degree of flexibility along with bracing all sections for possible movement. The code bracing requirements must be satisfied to provide for an approved seismic design.

Steel pipes less than 2 1/2 in diameter are often joined in threaded connections. Threaded connections can be unions, bends, or tees. Threaded connections are more vulnerable to shearing due to the removed volume at threaded pipe ends. Potential shear forces created at threaded connections should be limited by bracing.

RESIDENTIAL DESIGN

Copper pipes are joined with solder connections and provide for a long-lasting efficient system. Benefits of copper include its ductile properties as well as its lightweight. The ductility of copper helps to limit shear forces. Sufficient solder must be filled into copper joints to achieve strong bonds. A transfer from steel to copper piping noticeably reduces the imposed sprinkler line dead load on its supporting members. Since the introduction of CPVC sprinkler pipe, copper design has been phasing out of use in sprinkler designs.

When the sprinkler line changes to a lighter material all the required connection materials are sized to accommodate. Plastic piping is the lightest material used for sprinkler line, its weight is only a fraction of the fluid-filled system. Plastic fire sprinkler line is available as fire retardant PVC dubbed CPVC. In the current residential and light commercial areas CPVC installation has become the common trade practice. The popularity of CPVC is due to the speed and ease of installation as well as the long-term dependability. From structural dynamics I have learned by decreasing the imposed dead load on the roofs of structures a building will attract less earthquake forces. Combined with the obvious advantages to the speed of assembly, reduced material and labor costs, there's no question why many current designs use plastic.

Plastic PVC sprinkler pipes are joined using the appropriate bonding glue. Plastic systems ductile properties allow for rotation. Available rotations within the system serve to limit shear forces. PVC seismic bracing consists of plastic straps fixed to the structure as well as the secured bracing required by NFPA-13 code.

In residential systems where fire sprinkler installation commonly involves plastic or copper systems, static and dynamic support is provided by the small clamps used to stabilize the lines as they pass through rafters and floor joists. Because the systems often have short support spans, required pipe clearances become the main seismic design consideration.

4 BUILDING DESIGN

DESIGN

The model fits upon the 3' x 3' Dacron Shake Table. The symmetry of the model and table bolt connections offers two model placement possibilities. Either the model can be shaken along its long axis or can be rotated 90 degrees to shake along its short axis. The model had to be at best a small version of a real structure. The constructed model looks like an extra large "dog-house" with an overhanging gabled roof. The constructed model serves its purpose of providing a structure with distinct measurable natural periods and a platform for testing simple sprinkler designs. Due to a total weight about 500lb the model was equipped with steel straps that allowed it to be picked from above and wheels to roll on. By hoisting the model with the crane available in the lab, moving around the model was easily performed by one person.

CONSTRUCTION

The model is a timber structure. The studs, rafters, and floor joists are cut from 2x4 Douglas fir. The barge rafter and fascia board are cut from 2x6 Douglas fir. The sub-floor and roof sheathing are cut from 5/8 inch CDX plywood. Walls were sheeted with 1/2-inch structural plywood. The underside was sheeted with 1/2 inch CDX to provide a flat base. Six hold-downs were spaced every 16 inches along the two longest walls. Two more holes were drilled through the sub-floor to provide a total of eight bolted connections. High-grade 1/2-inch steel bolts of proper lengths are used as connections to the table.

DRAWINGS AND PHOTOS

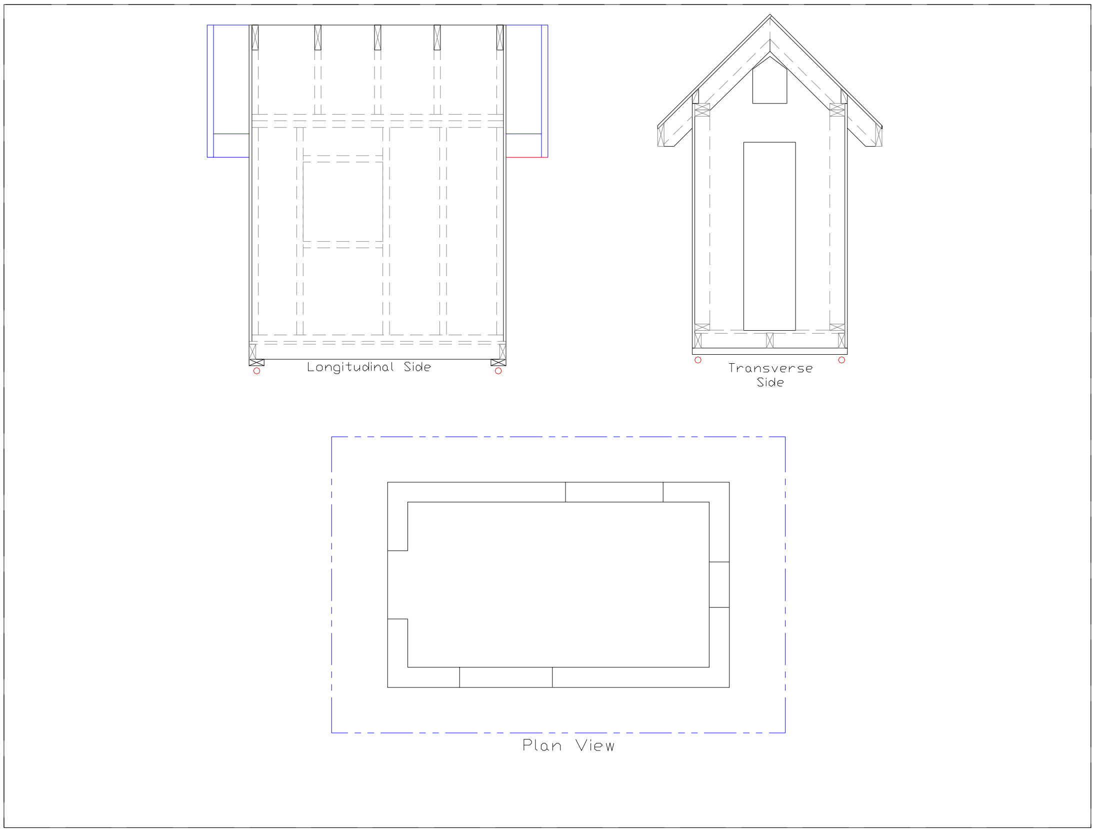


Figure 4 Drawing of Model (Scale 1/4" = 1')

Figure 5 Picture of Partially Completed Model

Figure 6 View of the Transverse Side with the Model Bolted onto Shake Table. The Model is plumbed with a Steel Sprinkler System

Figure 7 View of the Longitudinal Side with the Model Bolted onto Shake Table. The Workstation is Visible in the Background.

Figure 8 View of a hold-down from inside.

5 EXPERIMENTAL PROGRAM

SHAKE TABLE DESCRIPTION

The Shake table used for testing is bolted to the strong floor of the Dynamics Lab in Building 13 at Cal Poly State University. The Table consists of a three by three foot hydraulic platform driven by a separate motor and controlled by a workstation. Participating Software allows the workstation to record input from three separate data input channels. The first channel is dedicated for recording the base acceleration delivered to the shake table platform. The two remaining input channels allow for two acceleration data inputs per test run.

Base acceleration is applied in one direction only. Use of the Software allows for the input frequencies and the base acceleration to be programmed and for two recordings measuring acceleration data to be stored. The accelerometers were not designed to record accurately at low frequencies and the table hydraulics vibrated ate high frequencies. The frequency range for clean data was from 10-25 Hz. The Recorded data goes into a predetermined folder on the hard drive.

TESTS PERFORMED

Longitudinal Direction Shaking

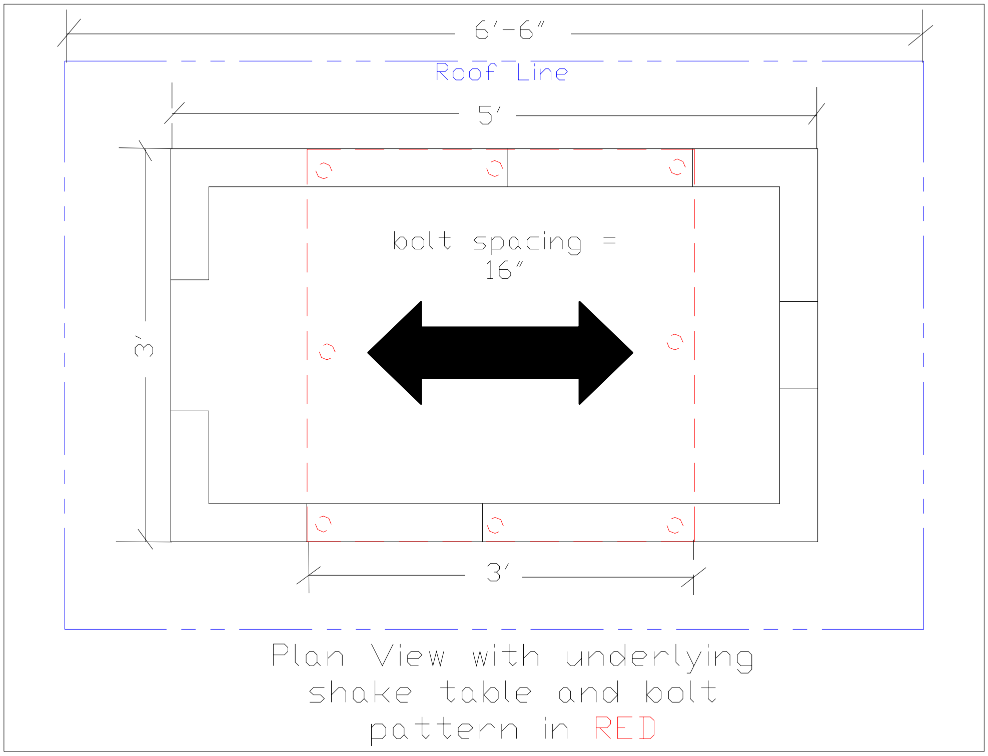


Figure 9 Model Placement for Longitudinal Testing

Transverse Direction Shaking

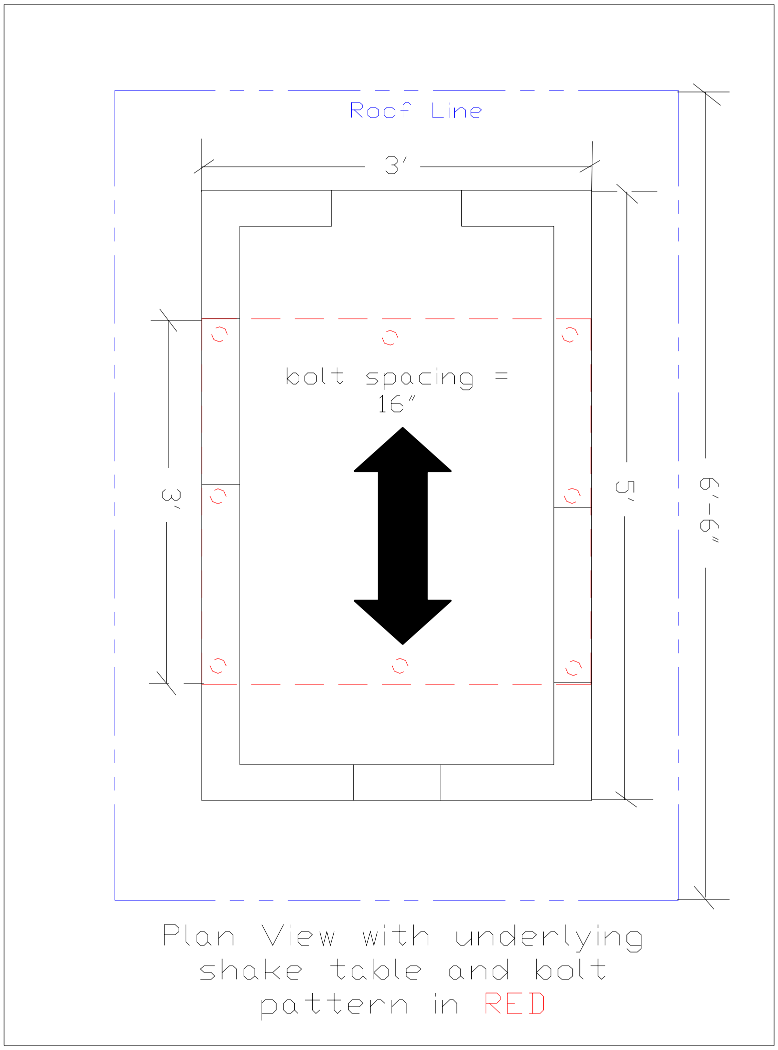


Figure 10 Model Placement for Transverse Testing

PLACEMENT OF ACCELEROMETERS

The accelerometers each recorded along the length of their tubular casing. The alignment of the accelerometers were set to the direction of shaking except for one placement that was set to record a vertical torsion response. Physical connection of the accelerometers involved using beeswax for adhesive and tape for added reinforcement. Cables ran from the accelerometers to the inputs of the workstation. The cables were secured with tape to the model so the cables weight wouldn't pull on the attached accelerometers during testing.

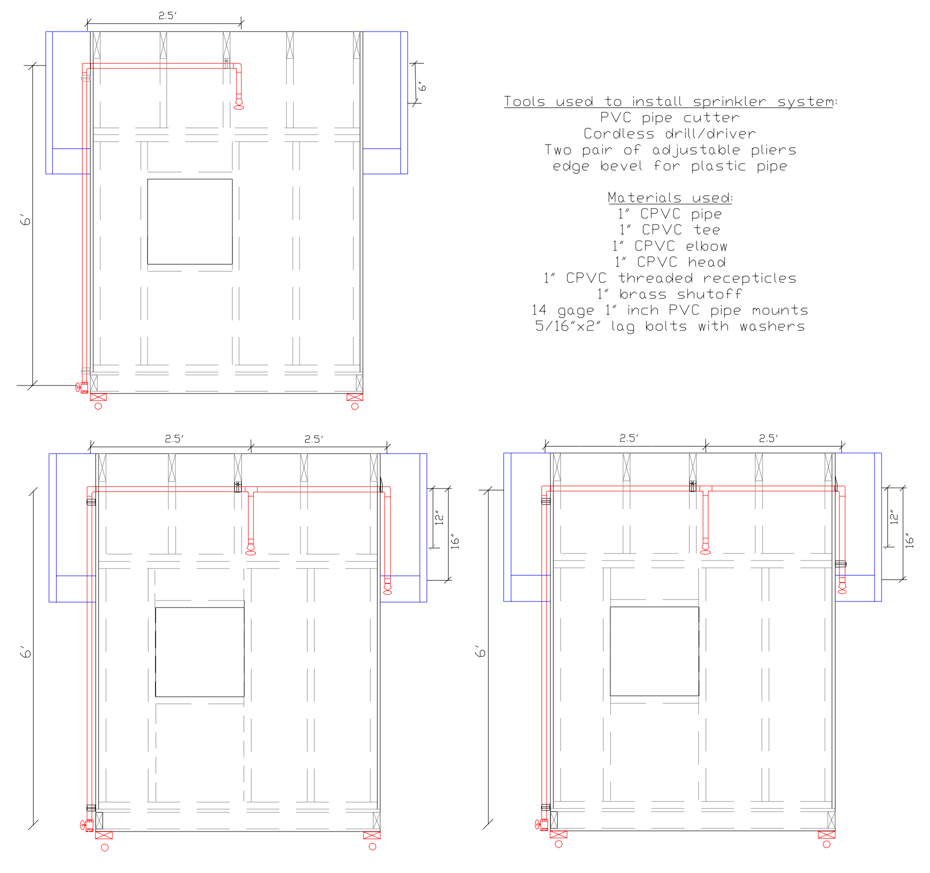
The decision on where to place accelerometers was based on particular points of interest. Test figures show the location and direction of the two acceleration readings with colored arrows that match the corresponding data series.

DIFFERENT SPRINKLER SYSTEMS CONSIDERED

The two types of sprinkler systems considered comprised of steel and CPVC. Today steel and CPVC are the most common materials used for sprinkler design. CPVC's introduction to the market has lessened installation costs and caused copper designs to become outdated. When a structures fire rating allows for a non-steel sprinkler design traditionally in the past copper systems were installed. In light commercial and residential sprinkler installations labor and material costs are saved when the design uses CPVC pipe verses copper pipe. The reduction in installation time for CPVC sprinkler systems compared to both steel and copper sprinkler systems is great because fitting are glued. By testing both steel and CPVC systems an understanding of the seismic properties associated with the different materials was gained.

CPVC Sprinkler System

A small sprinkler design was installed in the model. The first design included just one sprinkler drop. The second design extended the first to include a second drop. The third test design involved fixing the end drop to the model to prevent rotation of the head. A shut-off valve was installed at the model's base to hold water in the system. Threads were wrapped in teflon tape and spun into fittings using opposing pipe wrenches. The Sprinkler line was charged with water by adapting a garden hose to the shut-off valve connected to the hose bib in the lab. The one inch CPVC piping, required fittings, sprinkler heads, glue and required connectors were donated from Wayco Fire Protection and Alpha Fire Protection. The designs are shown in the following figure. Inserted next to the test set-up is a list of the tools and materials used for the sprinkler system assembly.



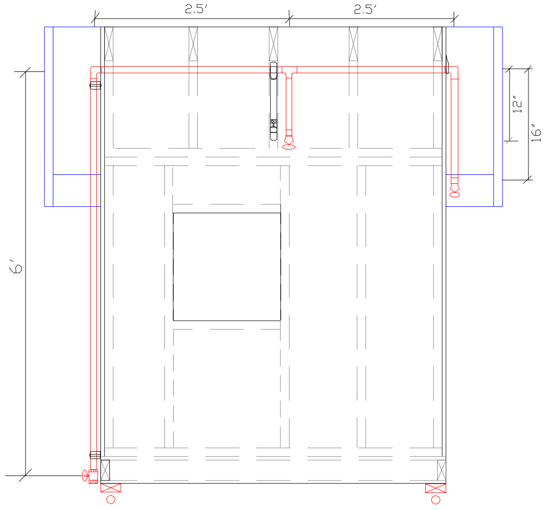
Tools used to install sprinkler system:
PVC pipe cutter
Cordless drill/driver
Two pair of adjustable pliers
edge bevel for plastic pipe

Materials used:
1″ CPVC pipe
1″ CPVC tee
1″ CPVC elbow
1″ CPVC head
1″ CPVC threaded recepticles
1″ brass shutoff
14 gage 1″ inch PVC pipe mounts
5/16″x2″ lag bolts with washers

Figure 11 CPVC Sprinkler System Designs

Steel Sprinkler System

The steel design tested copied the geometry of the double drop CPVC design. One inch steel pipes were donated, cut and threaded to length by Wayco Fire Protection. Wayco also provided all the steel fittings and the seismic restraint. Threads were wrapped in teflon tape and spun into fittings using opposing pipe wrenches. A shut-off valve was installed at the model's base to hold water in the system. The Sprinkler line was charged with water by adapting a garden hose to the shut-off valve connected to the hose bib in the lab. The one-inch seismic brace was fastened to the center rafter of the model. The brace was a diagonal pipe brace wrapped to the sprinkler line and pined to the rafter. The other pipe connectors used were vertical support hangers and one-inch pipe mounts for the two wall connections. The design is shown in the following figure. Inserted next to the test set-up is a list of the tools and materials used for the sprinkler system assembly.



Tools Used To Install Sprinkler System
Pipe Cutter
Pipe Threader
2 Pipe Wrenches
Adjustable Wrench
Cordless Drill/Driver

Materials Used
1″ Schedule 40 Steel Pipe
1″ Steel Tee
1″ Steel Elbow
1″ Steel Head
1″ Brass Shut-Off Valve
14 Gauge Pipe Mounts
1″ Seismic Restraint
5/16″x2″ Lag Bolt and Washer

Figure 12 Steel Sprinkler System Design

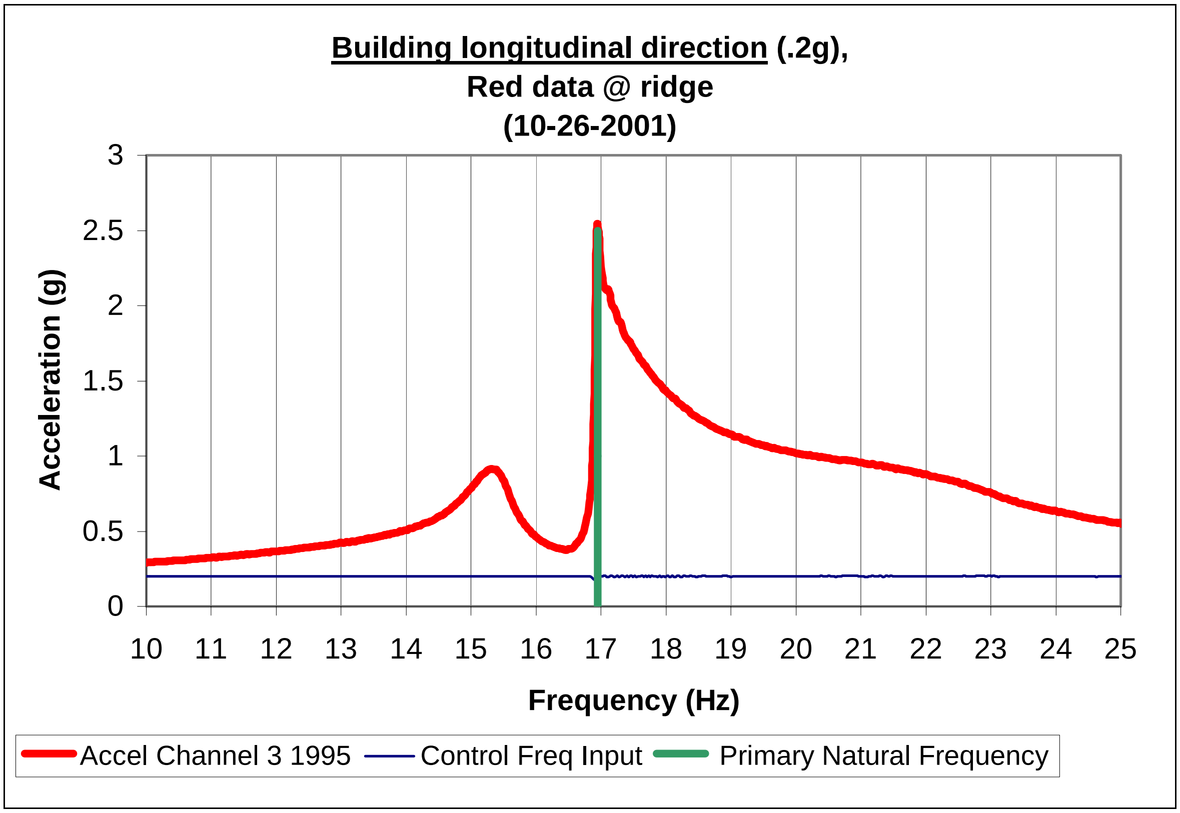
Figure 13 Threading Steel Pipe

6 DYNAMIC PROPERTIES OF BUILDING

For each of the two test directions the building had pronounced natural frequencies. Recorded acceleration data at locations identified by drawings are presented in the following. The two sections are tests grouped according to the model's shaking direction.

The first tests on the model were done using input accelerations of 0.1 - 0.2(g) at the base. Once comfortable with the structural integrity of the model tests were run as high as 0.5(g). At the higher input base acceleration levels, the attached sprinkler systems achieved such a great level of observed and recorded amplification that, going any higher was not done for fear of failing the building or the sprinkler system. The main reason for not wanting to fail the building it was needed for following tests. Now that fire sprinkler testing has been performed the Civil Engineering Department can use the building for further testing of attached mechanics or any other interior component. The stable design of the timber building allowed it to withstand all tests without any sign of damage. Assumedly the building would absorb much greater base accelerations before reaching structural failure. Average seismic designs use an expected seismic acceleration value of 0.4(g).

FIRST FUNDAMENTAL FREQUENCY IN LONGITUDINAL DIRECTION



Graph 1 Building Test in Longitudinal Direction (10-26-01)

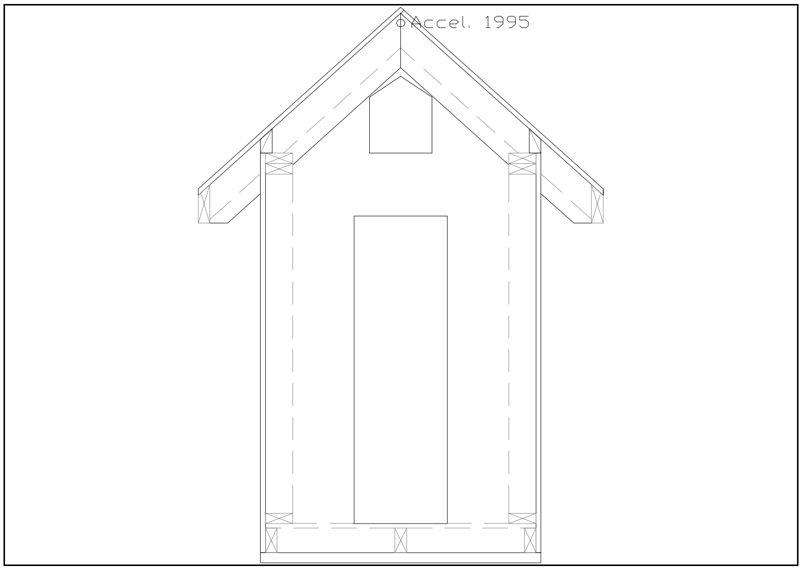
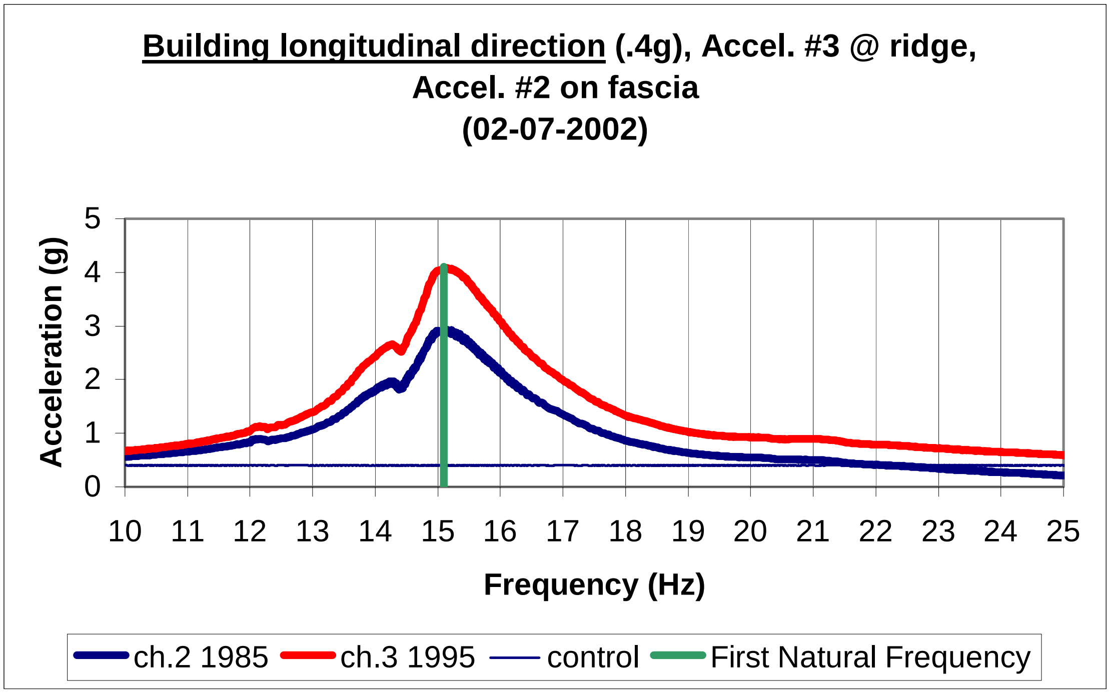


Figure 14 Placement of Accelerometer in Graph 1



Graph 2 Building Test in Longitudinal Direction (02-07-02)

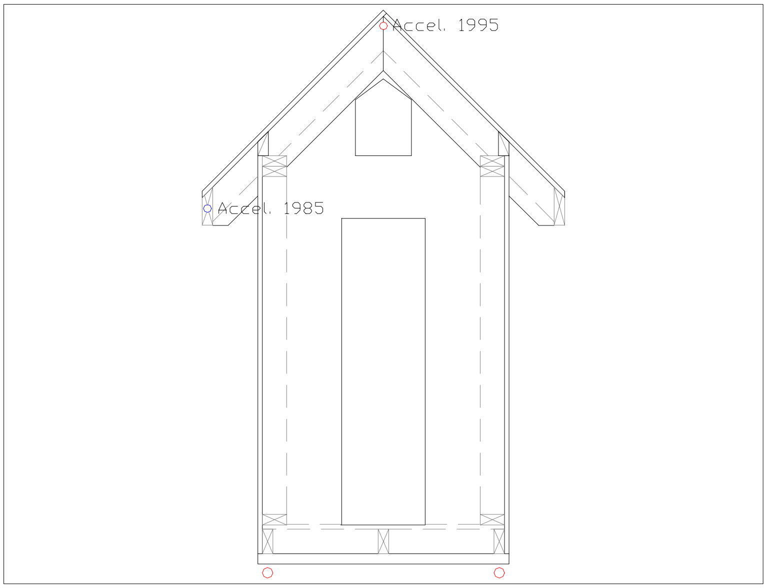
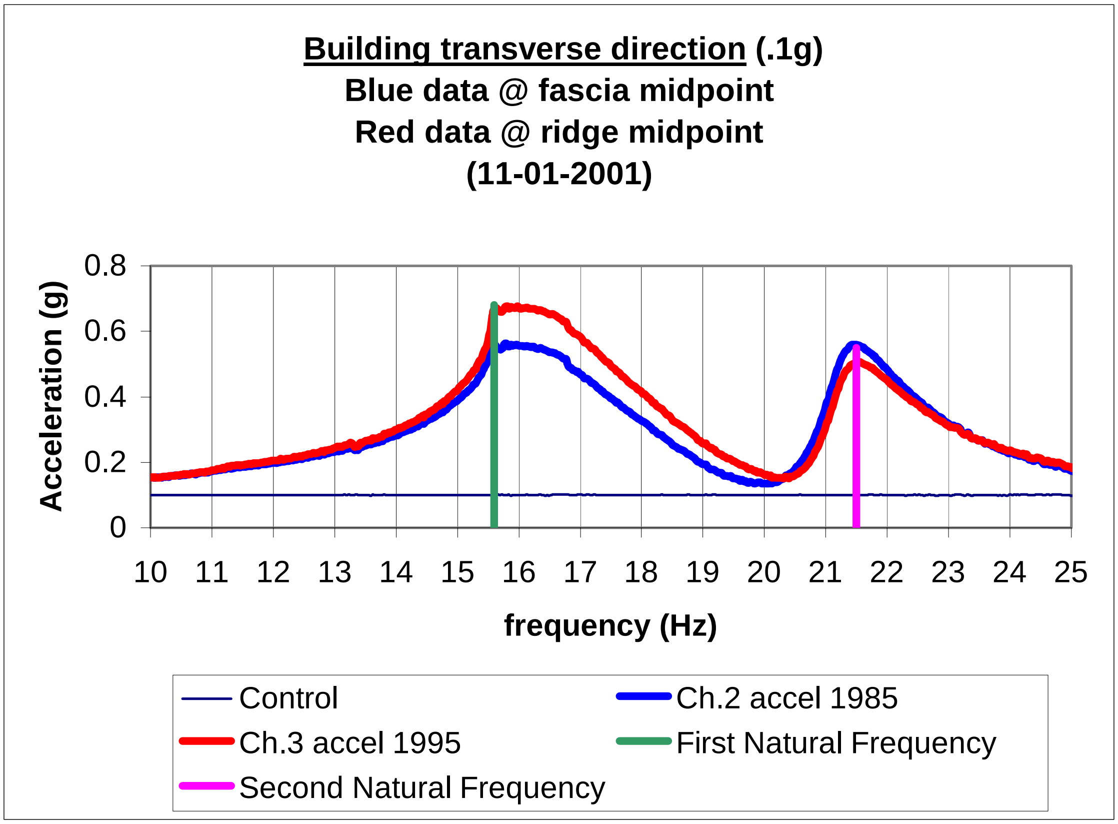


Figure 15 Placement of Accelerometers in Graph 2

FIRST 2 FUNDAMENTAL FREQUENCIES IN TRANSVERSE DIRECTION



Graph 3 Building Test in Transverse Direction (11-01-01)

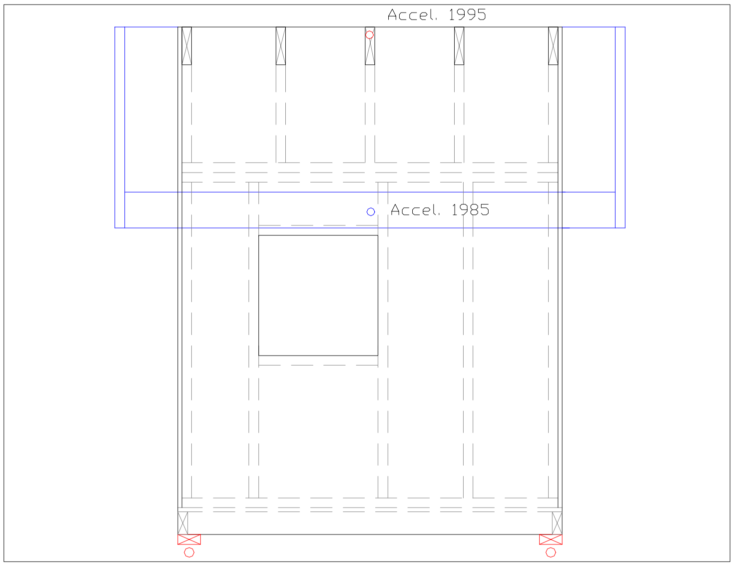
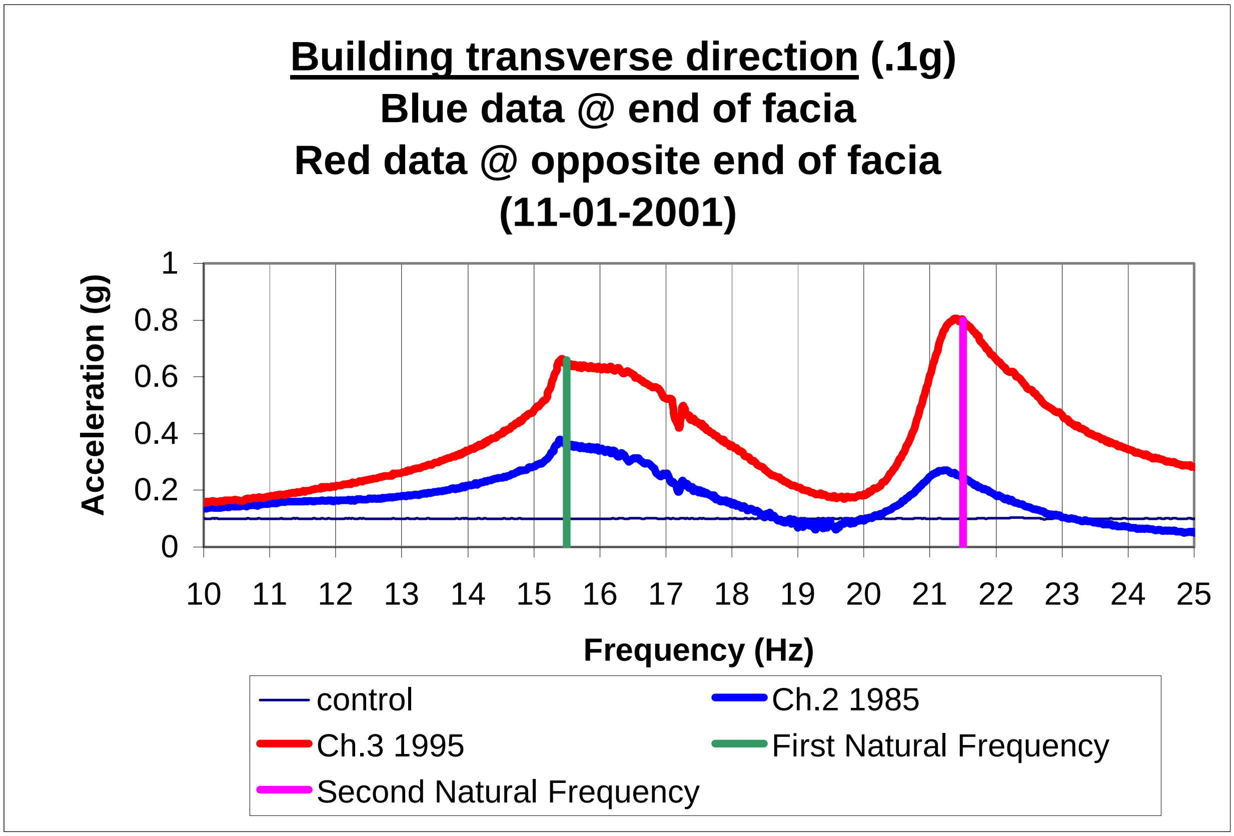


Figure 16 Placement of Accelerometers in Graph 3



Graph 4 Building Test in Transverse Direction (11-01-01)

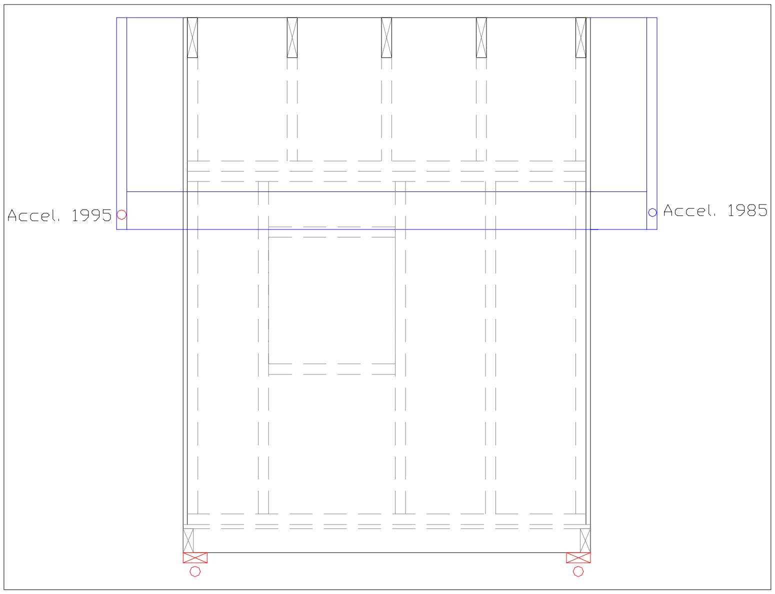
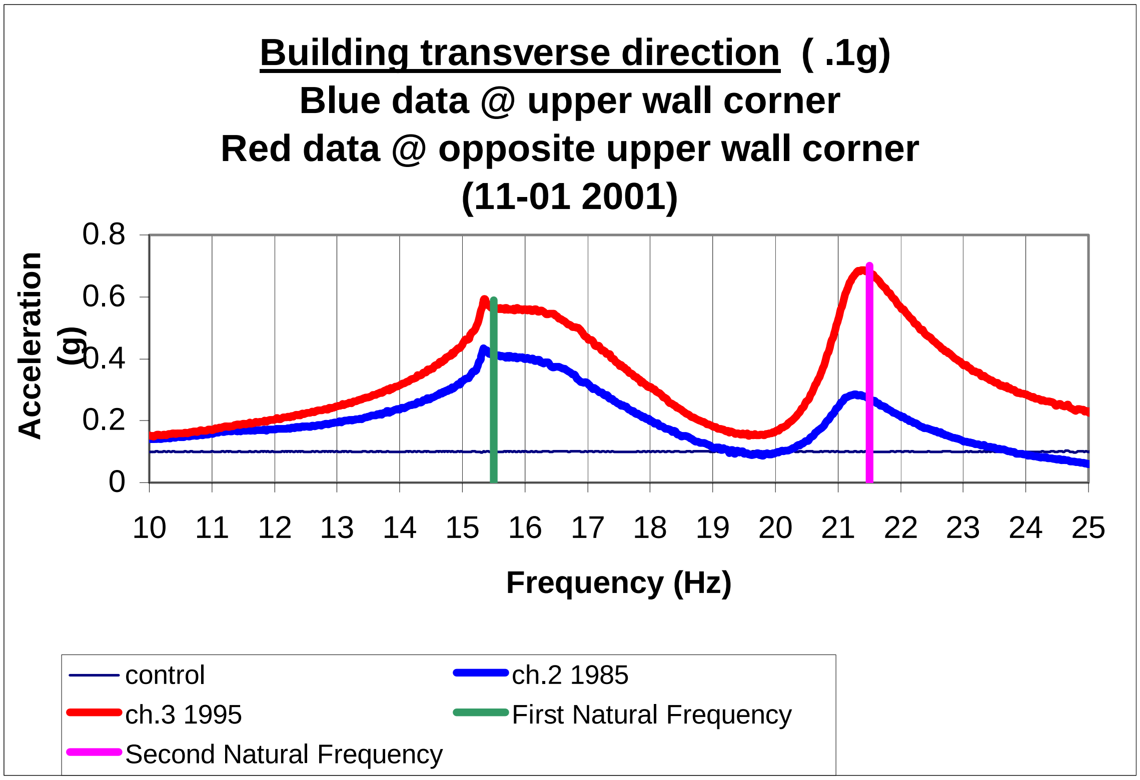


Figure 17 Placement of Accelerometers in Graph 4



Graph 5 Building Test in Transverse Direction (11-01-01)

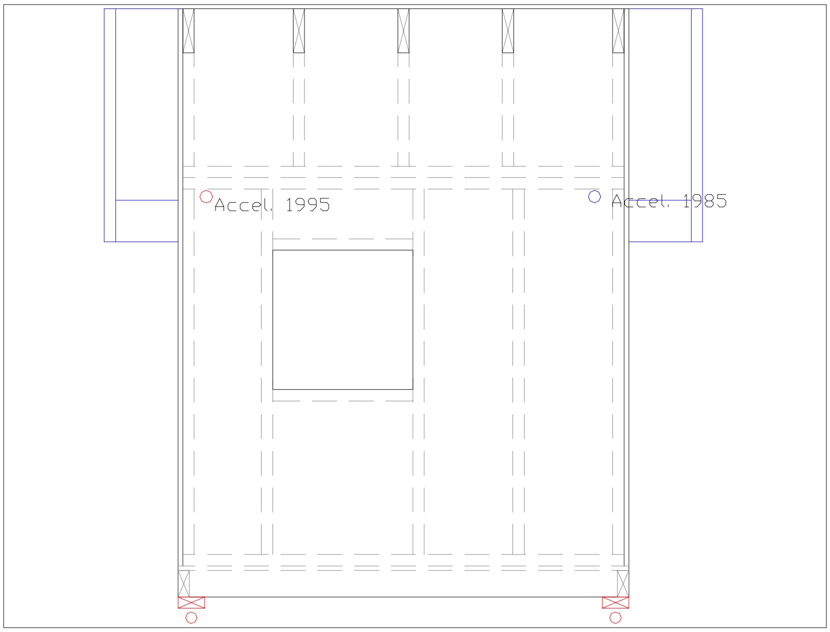
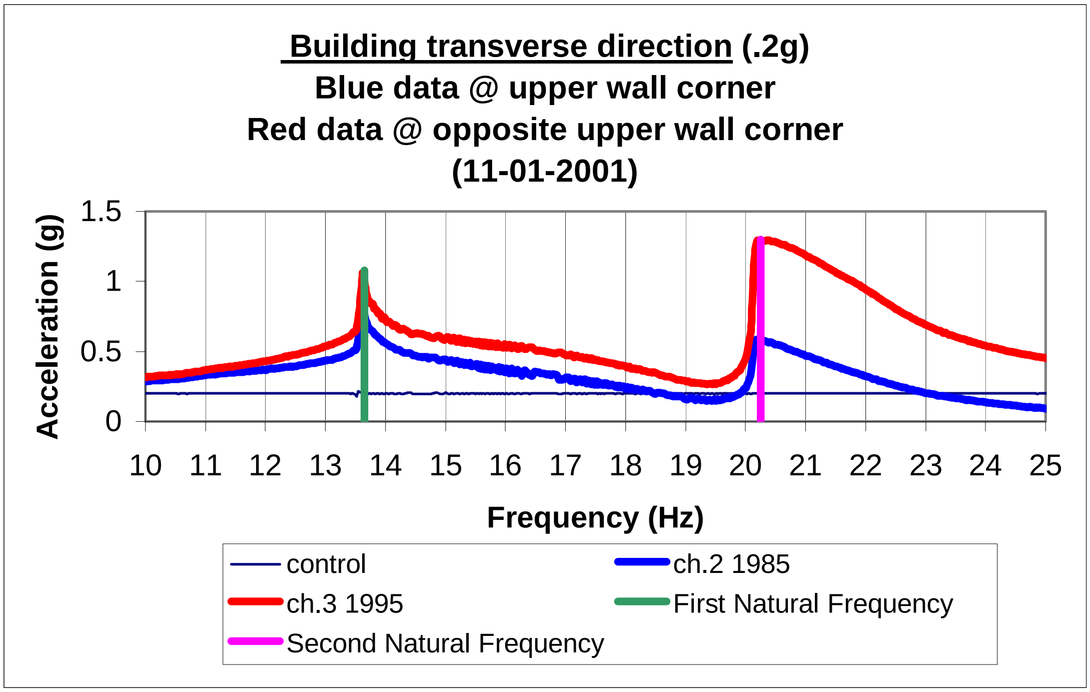


Figure 18 Placement of Accelerometers in Graph 5



Graph 6 Building Test in Transverse Direction (11-01-01)

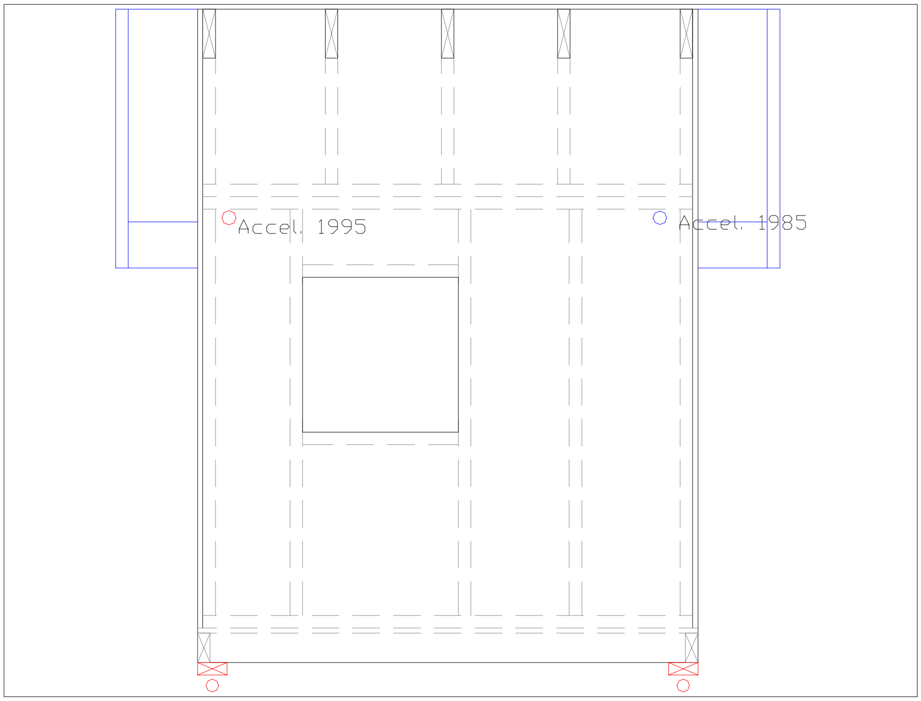


Figure 19 Placement of Accelerometers in Graph 6

BUILDING TEST RESULTS

Table 1 Fundamental Frequencies of The Building

Test Direction	**Base Acceleration**	**Natural Frequency**	**Location(s) of Recording**	**Maximum Amplification**
Longitudinal	0.2 g	16.9 Hz	Ridge	12x
Longitudinal	0.4 g	15.2 Hz	Fascia, Ridge	10x
Transverse	0.1 g	15.5, 21.5 Hz	Fascia, Ridge	7x
Transverse	0.1 g	15.5, 21.5 Hz	Rafter Tails	8x
Transverse	0.1 g	15.5, 21.5 Hz	Wall Corners	7x
Transverse	0.2 g	13.7, 20.3 Hz	Wall Corners	7x

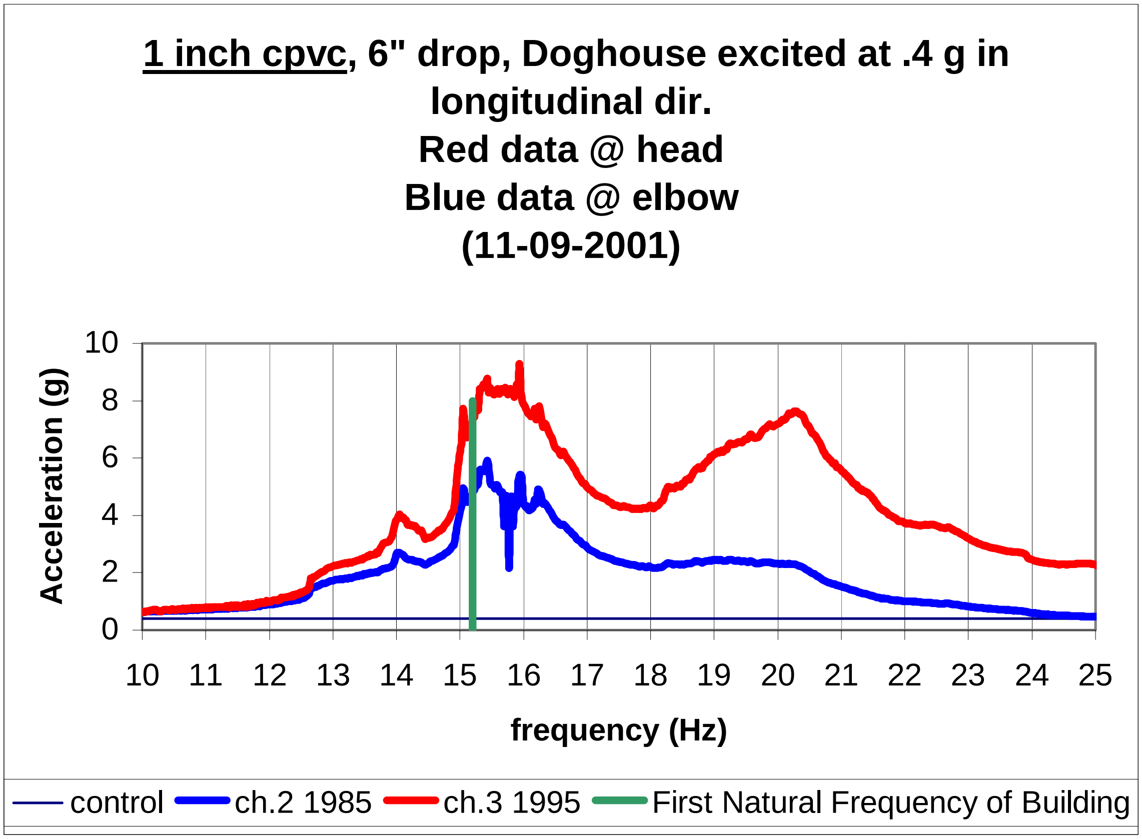
A natural frequency shift towards lower values occurred as the base acceleration increased. The two longitudinal tests show comparisons between both a change in input acceleration and testing at different times. The transverse tests were all performed in the early stages of testing before the model was fit with sprinkler systems. The building received numerous shakings over the course of testing that has likely caused the natural frequencies to lower slightly as the building loosened. In the following sprinkler system data, accelerometers were not available to register the building accelerations along with the sprinkler line accelerations. The buildings natural frequencies from the two highest base accelerations are used to represent the building contribution to each of the following sprinkler system graphs.

7 DYNAMIC PROPERTIES OF CPVC SPRINKLERS

DESCRIPTION OF TEST SET-UPS

The tested design involved bringing the sprinkler line up the back of the model through the opening under the eve and into the inside. The first set-up had one small drop plumbed in the middle of the model's interior. The second CPVC design doubled the center drop in length and included a longer drop run down the front face of the model. The final third plumbed design was the second design altered to test the effects of increasing the system restraints. The following data was recorded at both ends of fire system drops.

LONGITUDINAL DATA



Graph 7 Test of CPVC Sprinkler Design 1 (11-09-01)

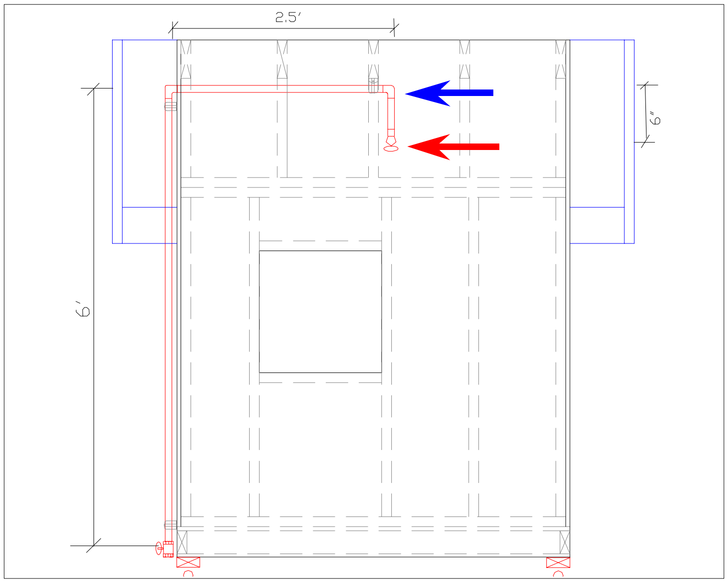
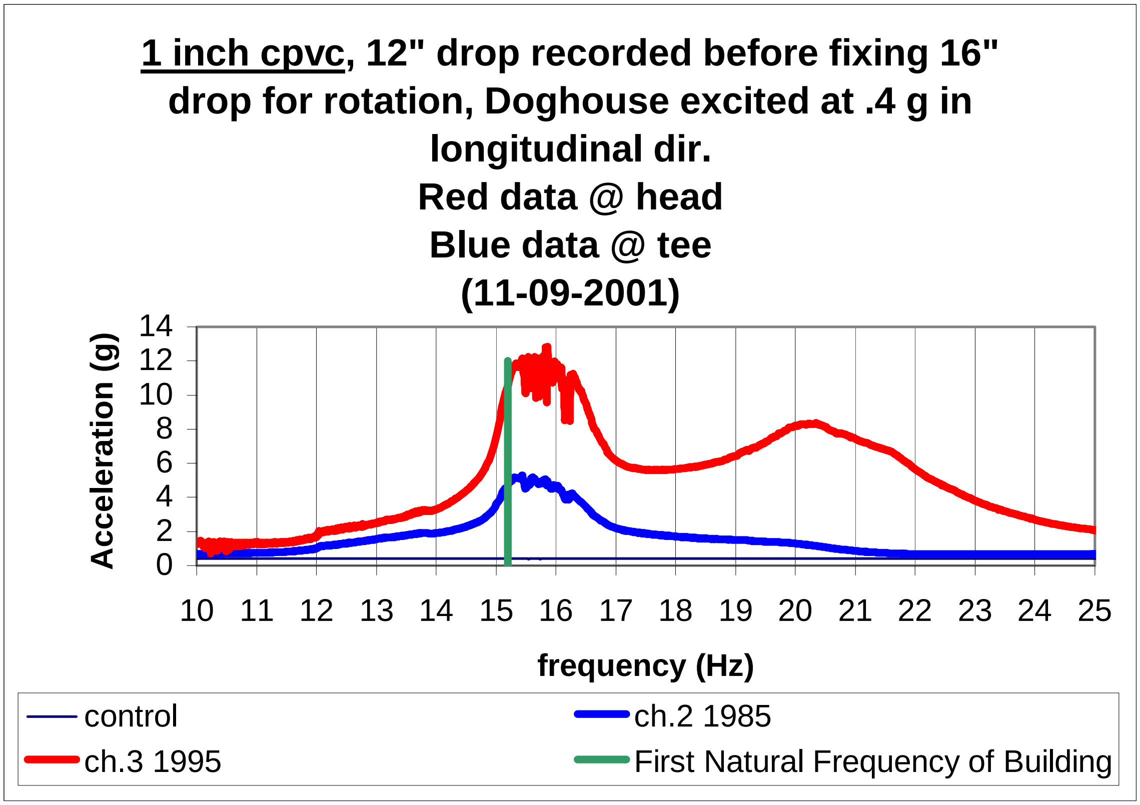


Figure 20 The Placement of the Accelerometers for Graph 7



Graph 8 Test of CPVC Sprinkler Design 2 (11-09-01)

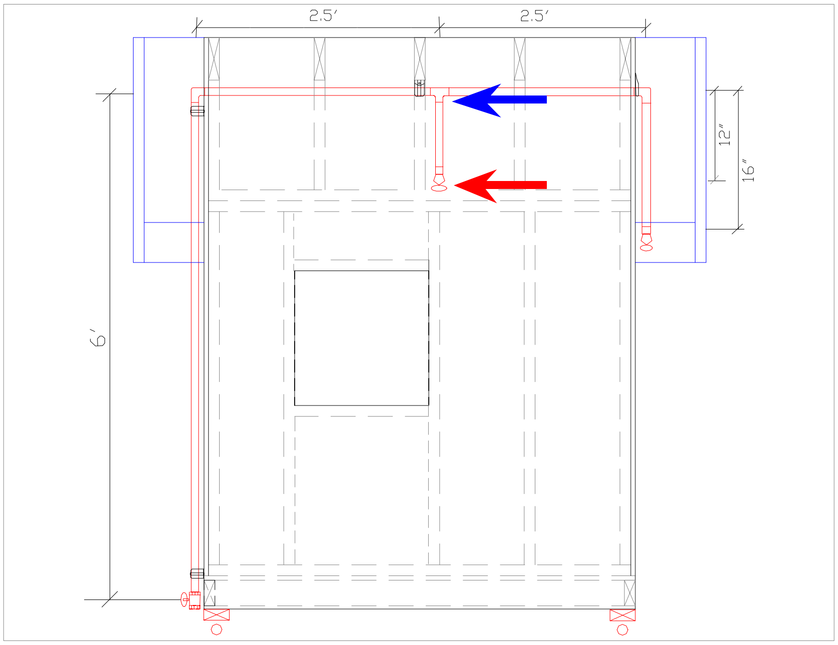
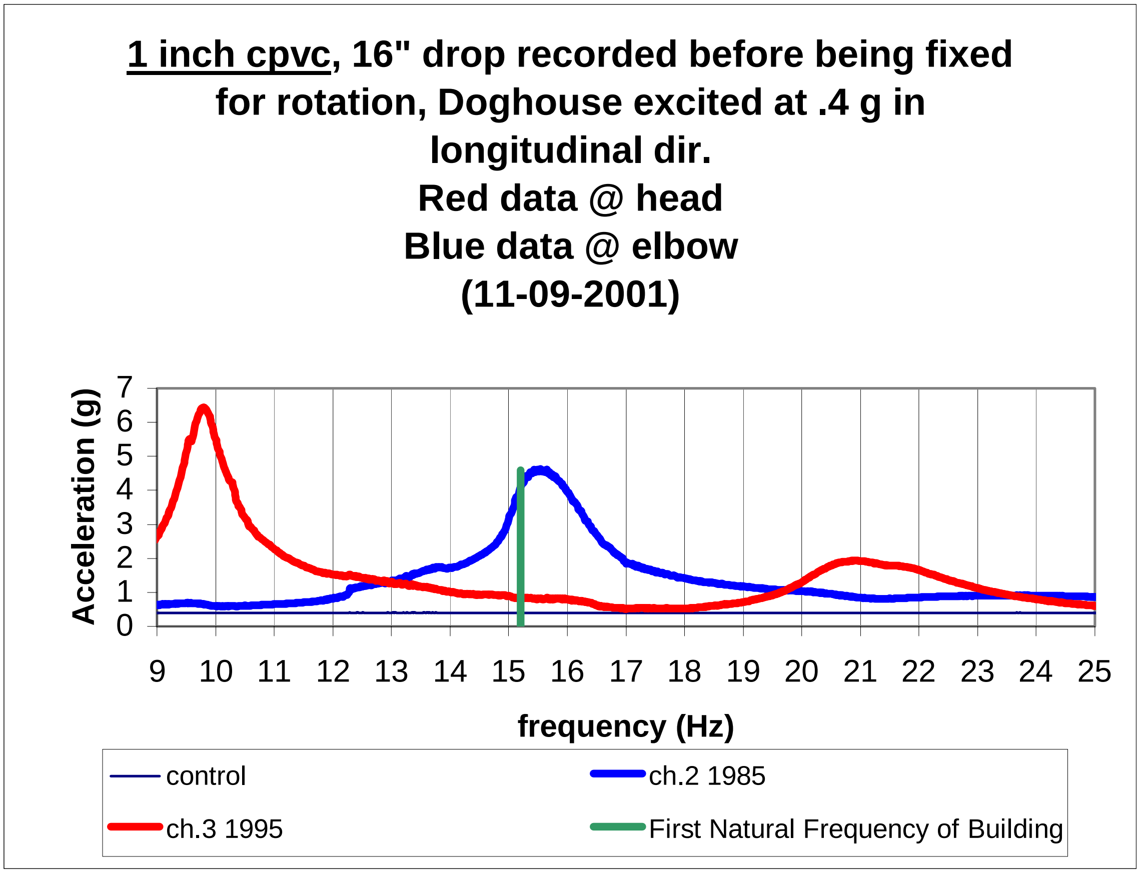


Figure 21 The Placement of the Accelerometers for Graph 8



Graph 9 Test of CPVC Sprinkler Design 2 (11-09-01)

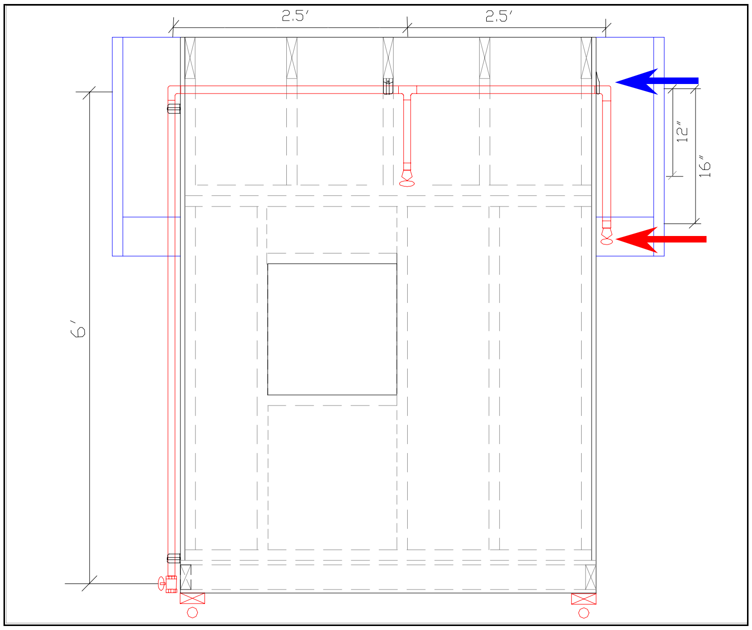
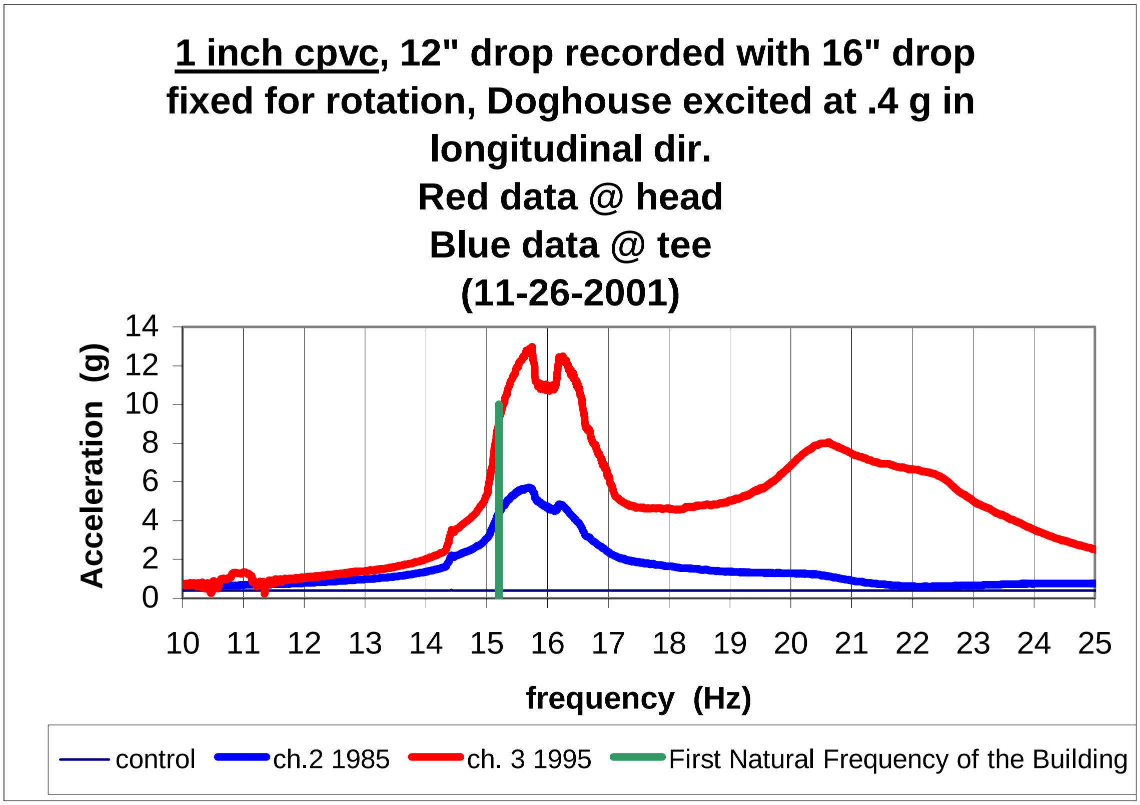


Figure 22 The Placement of the Accelerometers for Graph 9



Graph 10 Test of CPVC Sprinkler Design 3 (11-26-01)

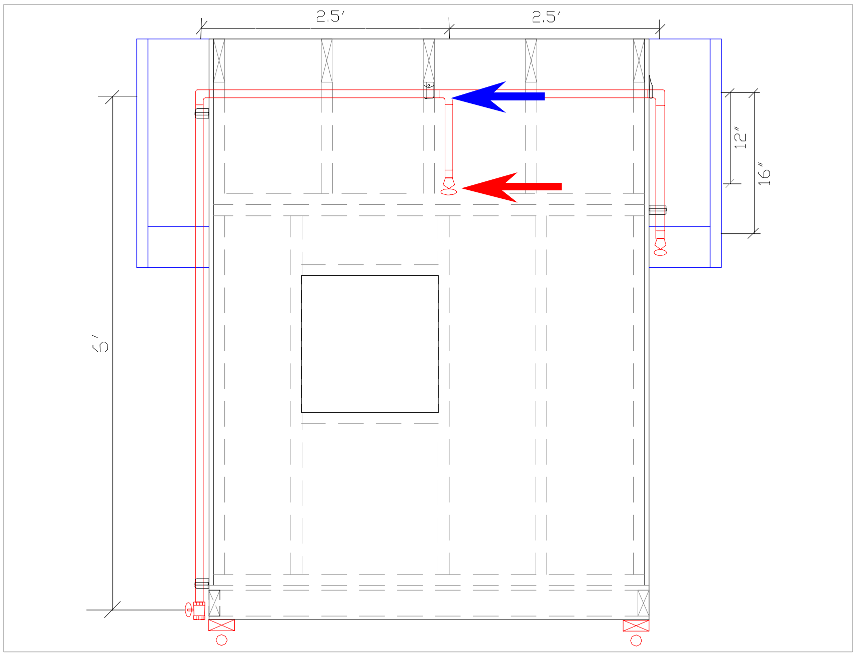
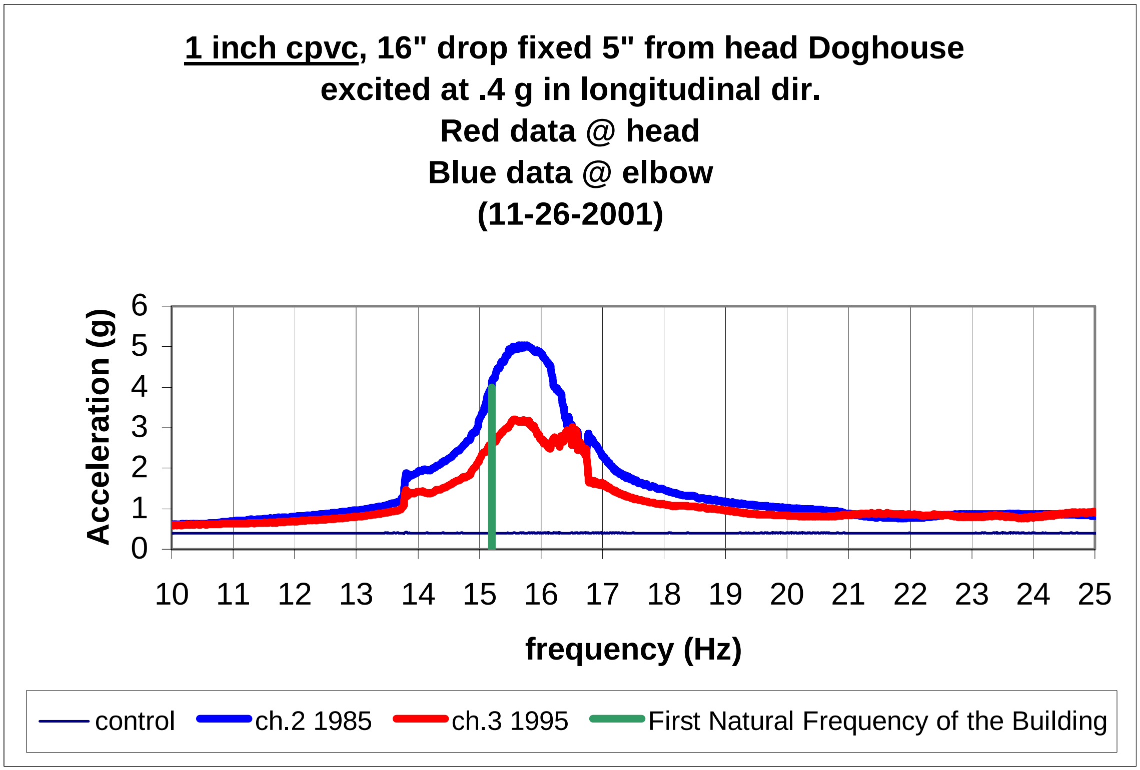


Figure 23 The Placement of Accelerometers for Graph 10



Graph 11 Test of CPVC Sprinkler Design 3 (11-26-01)

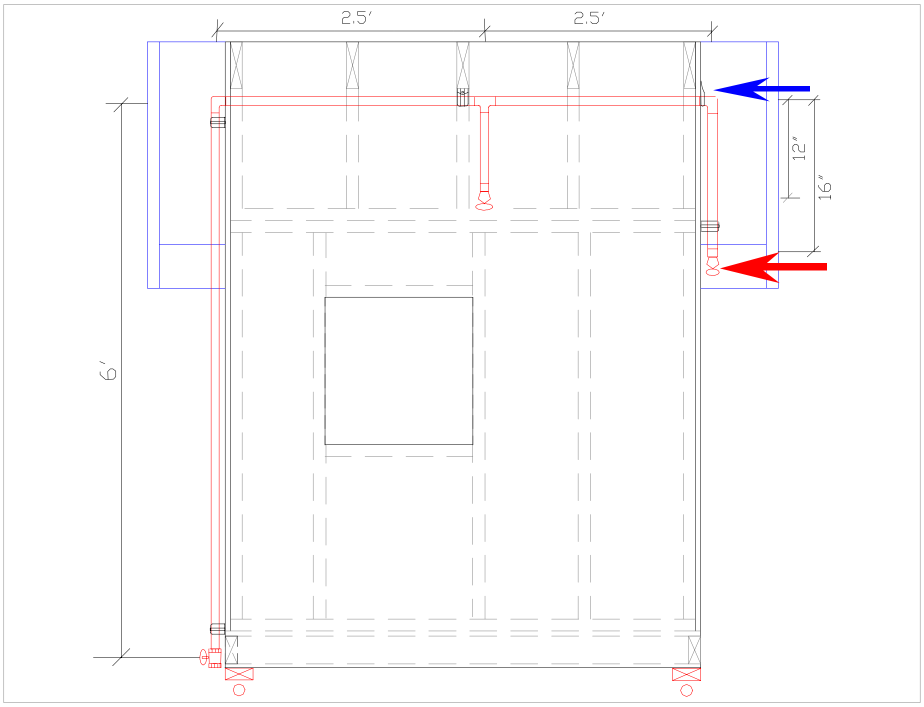
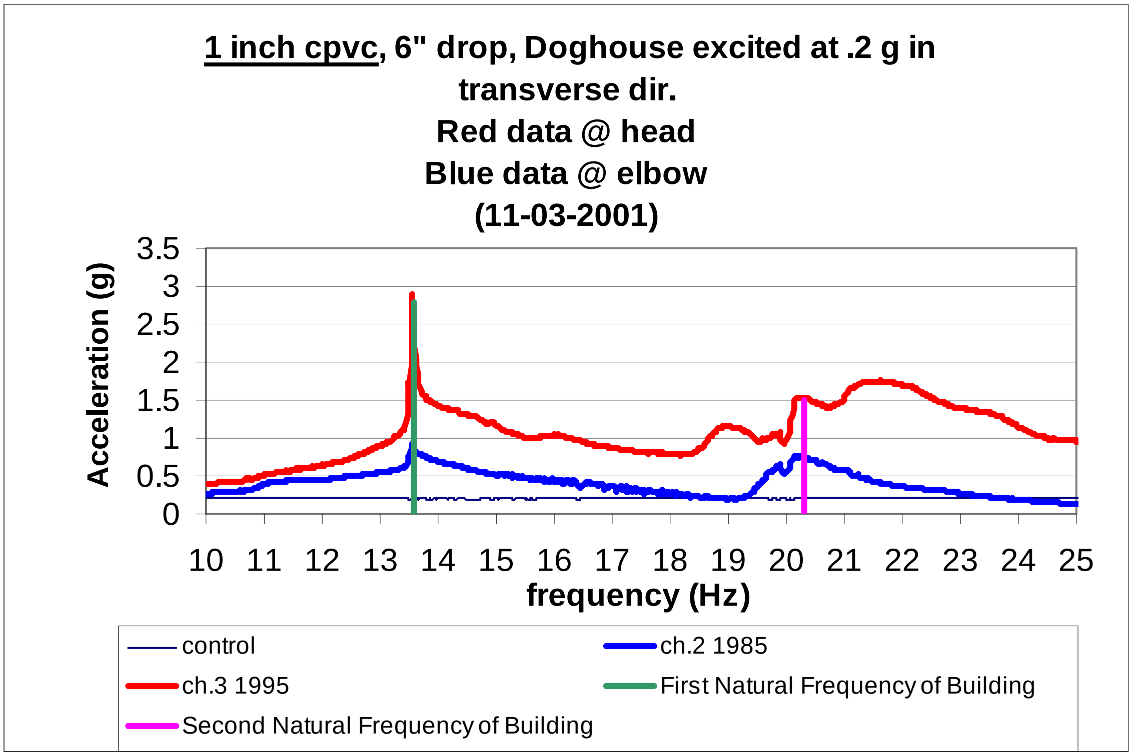


Figure 24 The Placement of the Accelerometers for Graph 11

TRANSVERSE DATA



Graph 12 Test of CPVC Sprinkler Design 1 (11-03-01)

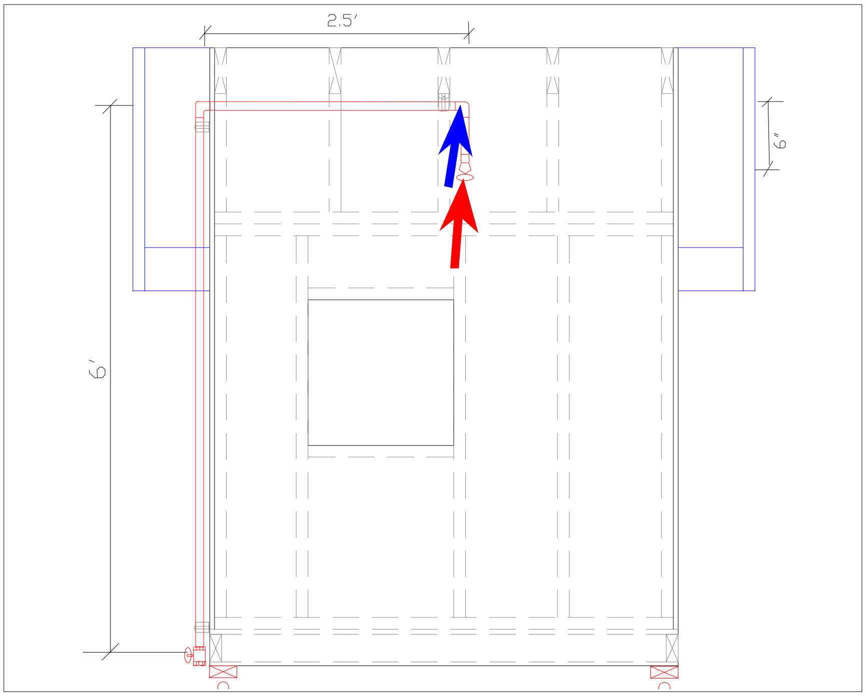
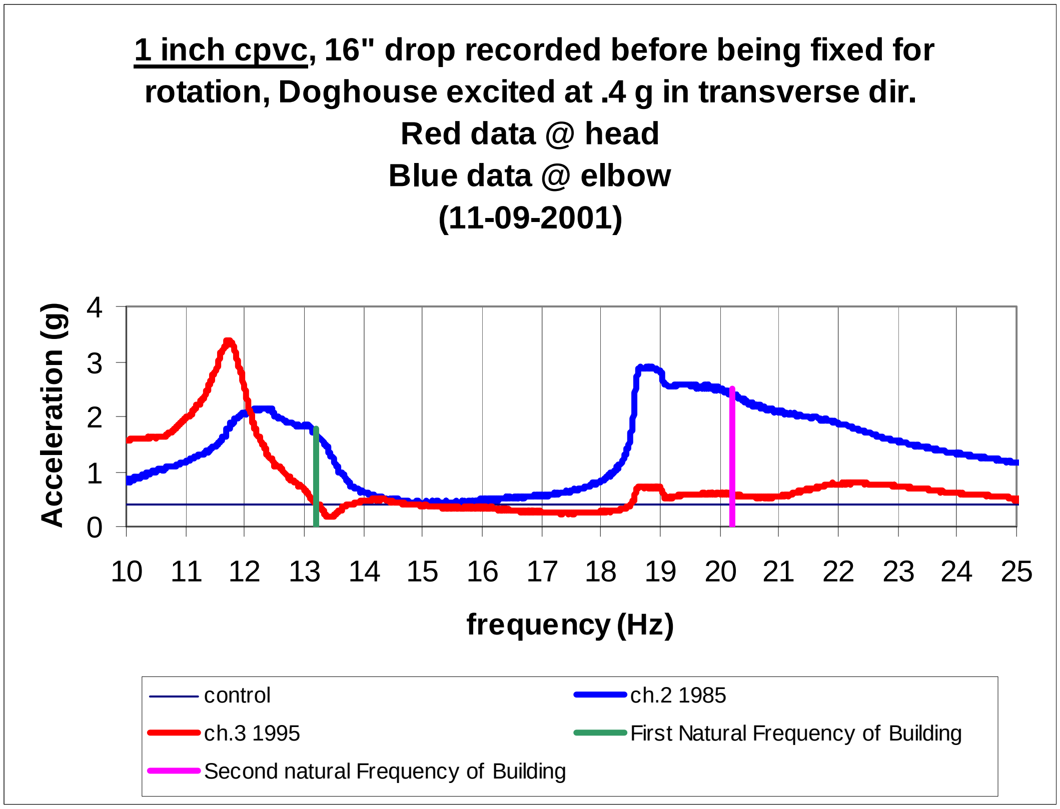


Figure 25 The Placement of the Accelerometers for Graph 12



Graph 13 Test of CPVC Sprinkler Design 2 (11-09-01)

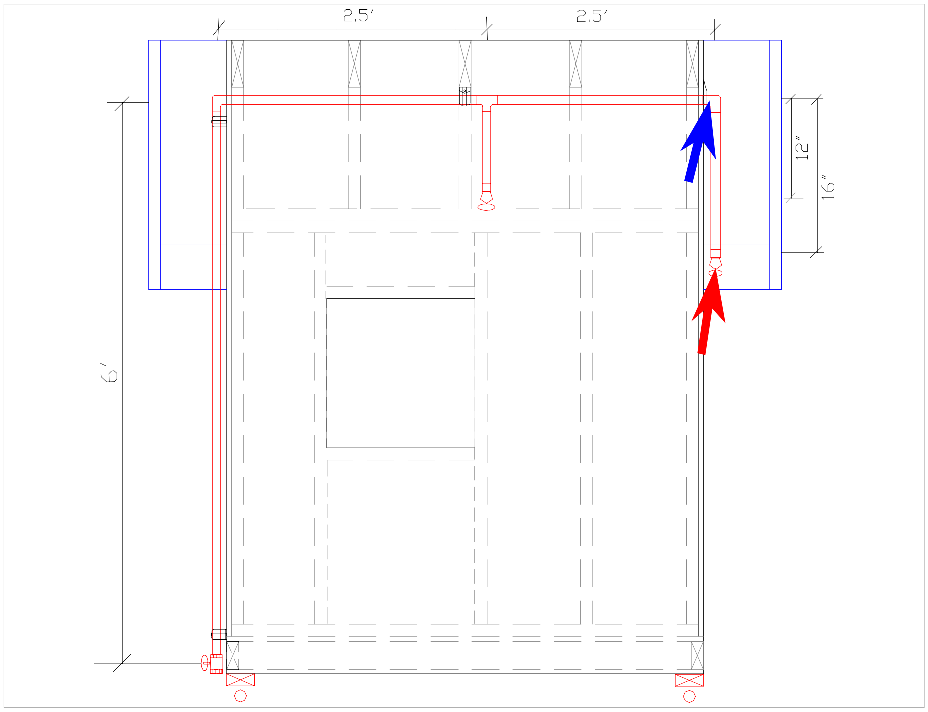
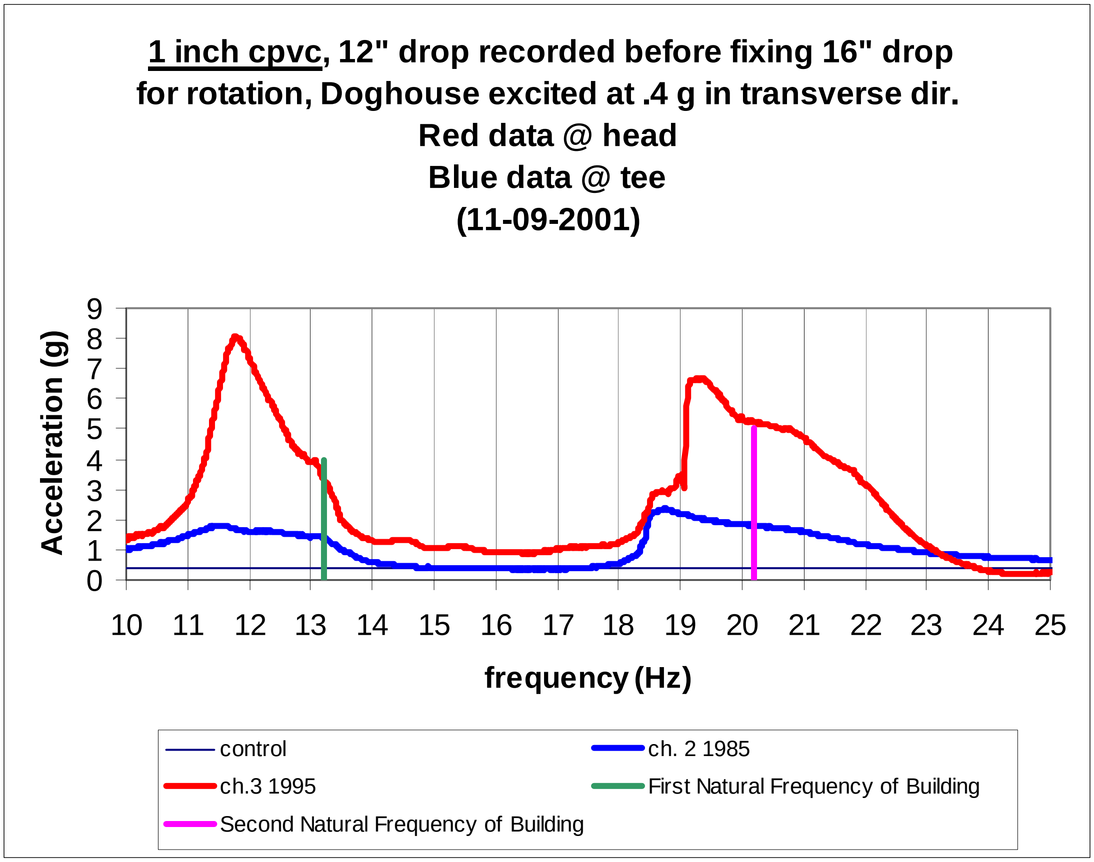


Figure 26 The Placement of the Accelerometers for Graph 13



Graph 14 Test of CPVC Sprinkler Design 2 (11-09-01)

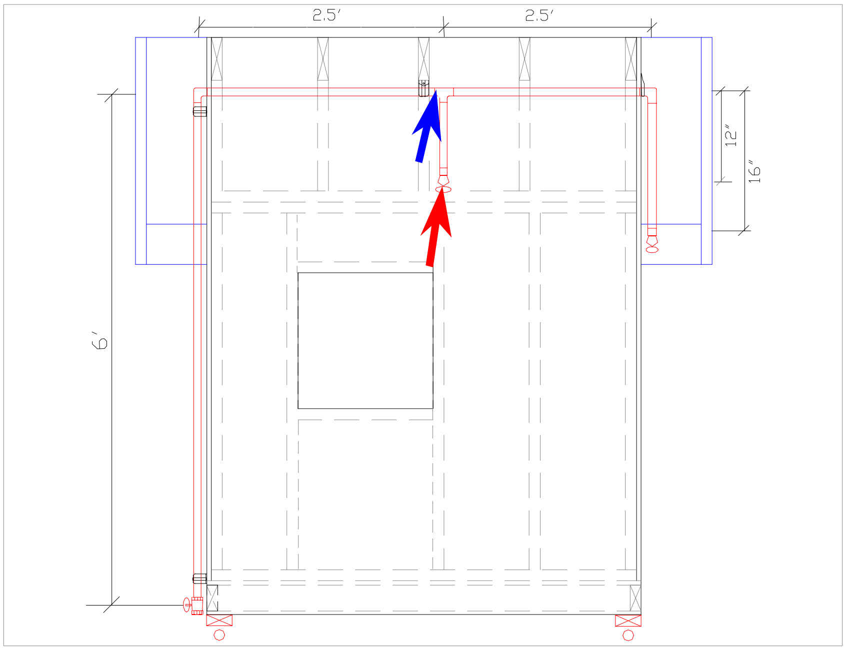
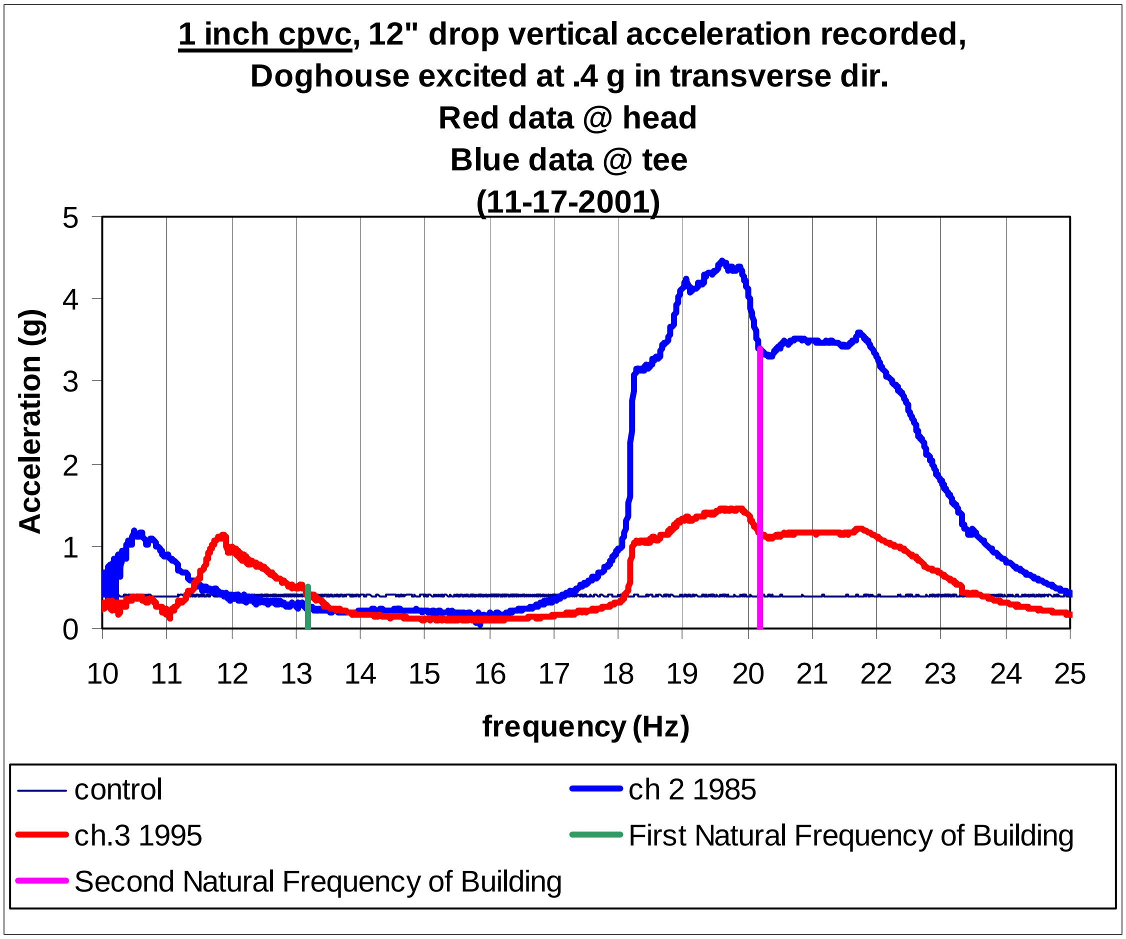


Figure 27 The Placement of the Accelerometers for Graph 16



Graph 15 Test of CPVC Sprinkler Design 2 (11-17-01), a Recording of the Vertical Acceleration

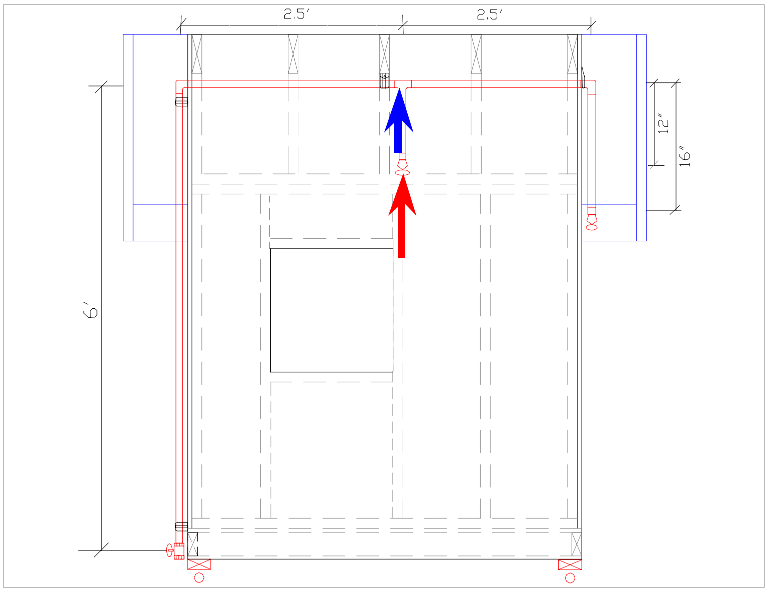
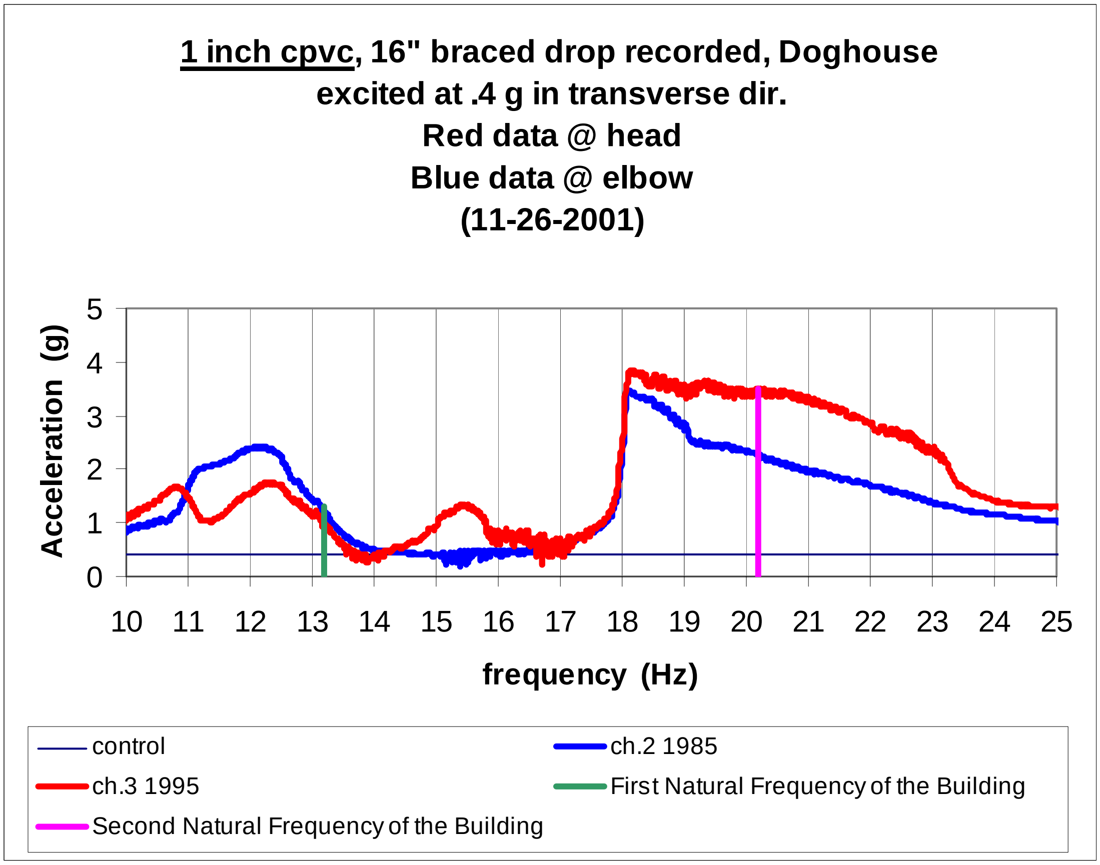


Figure 28 The Placement of the Accelerometers for Graph 15



Graph 16 Test of CPVC Sprinkler Design 2 (11-26-01)

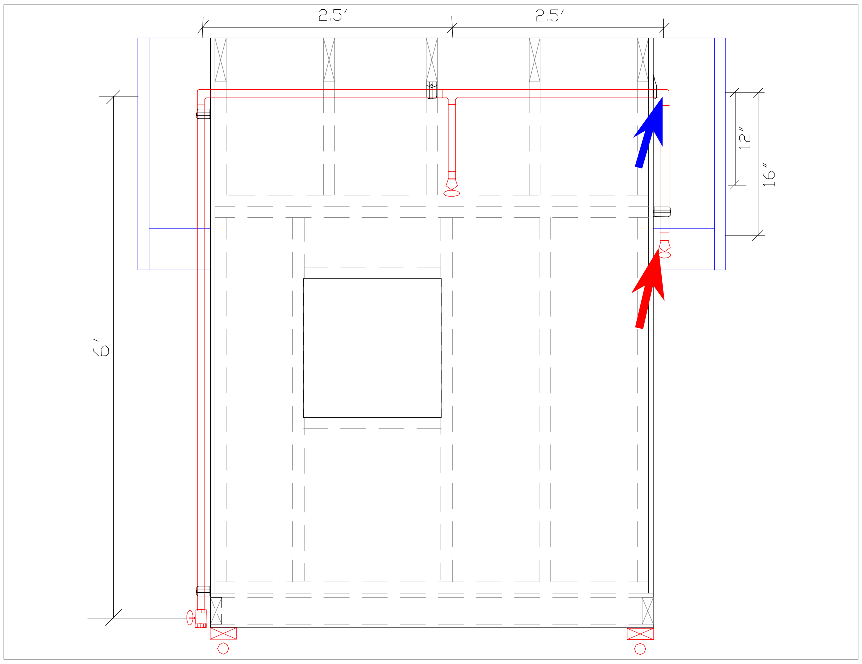
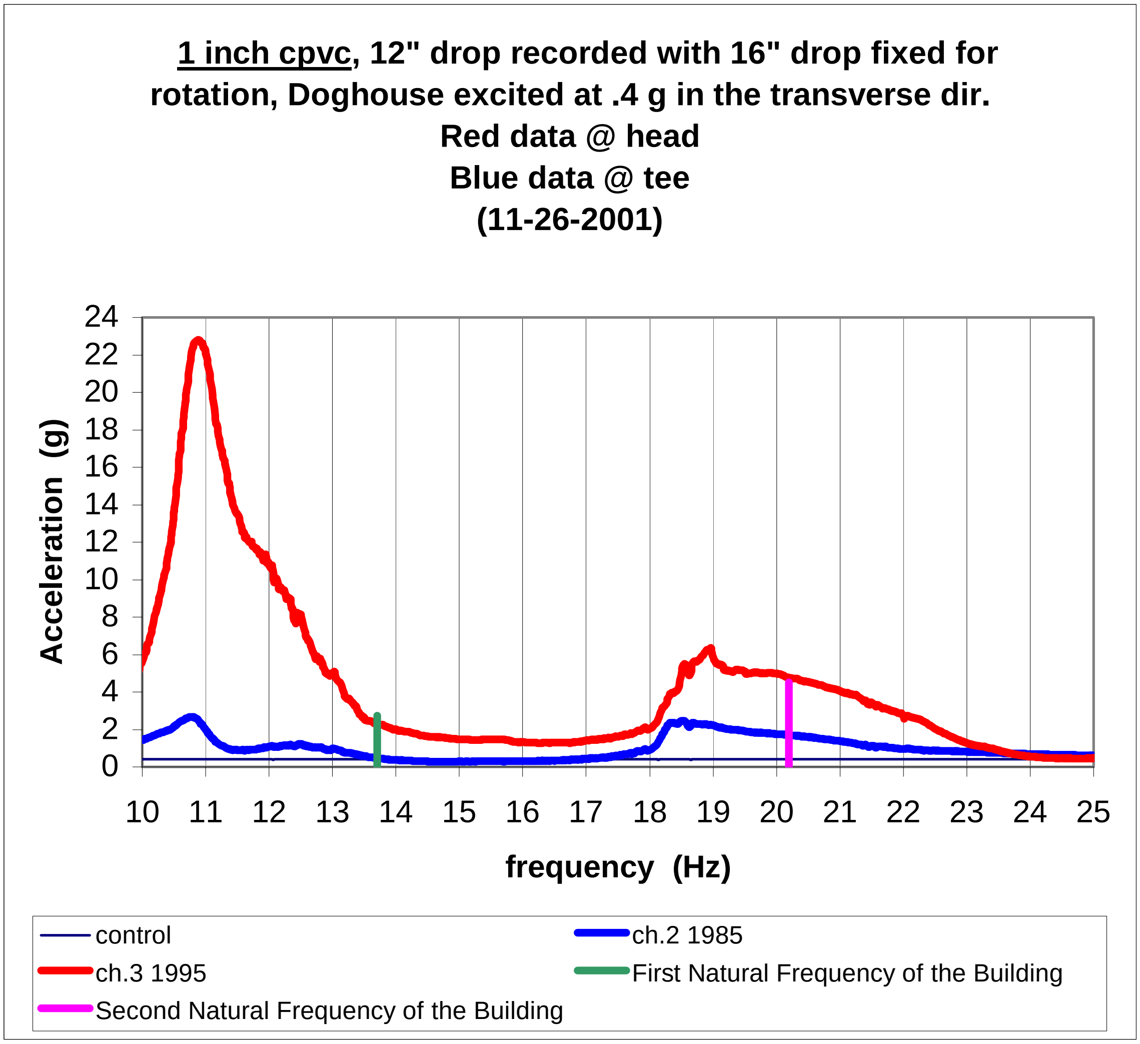


Figure 29 The Placement of the Accelerometers for Graph 16



Graph 17 Test of CPVC Sprinkler Design 3 (11-26-01)

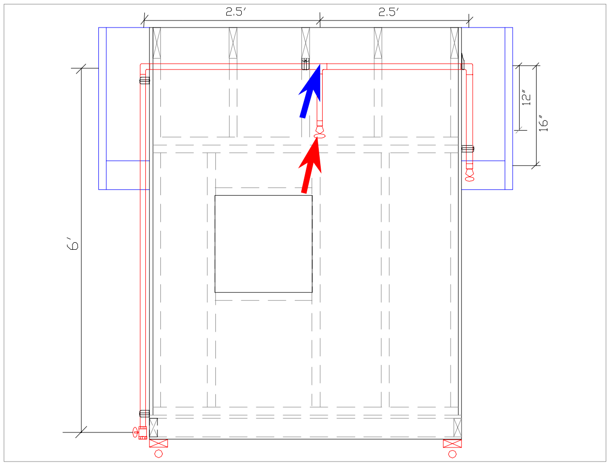
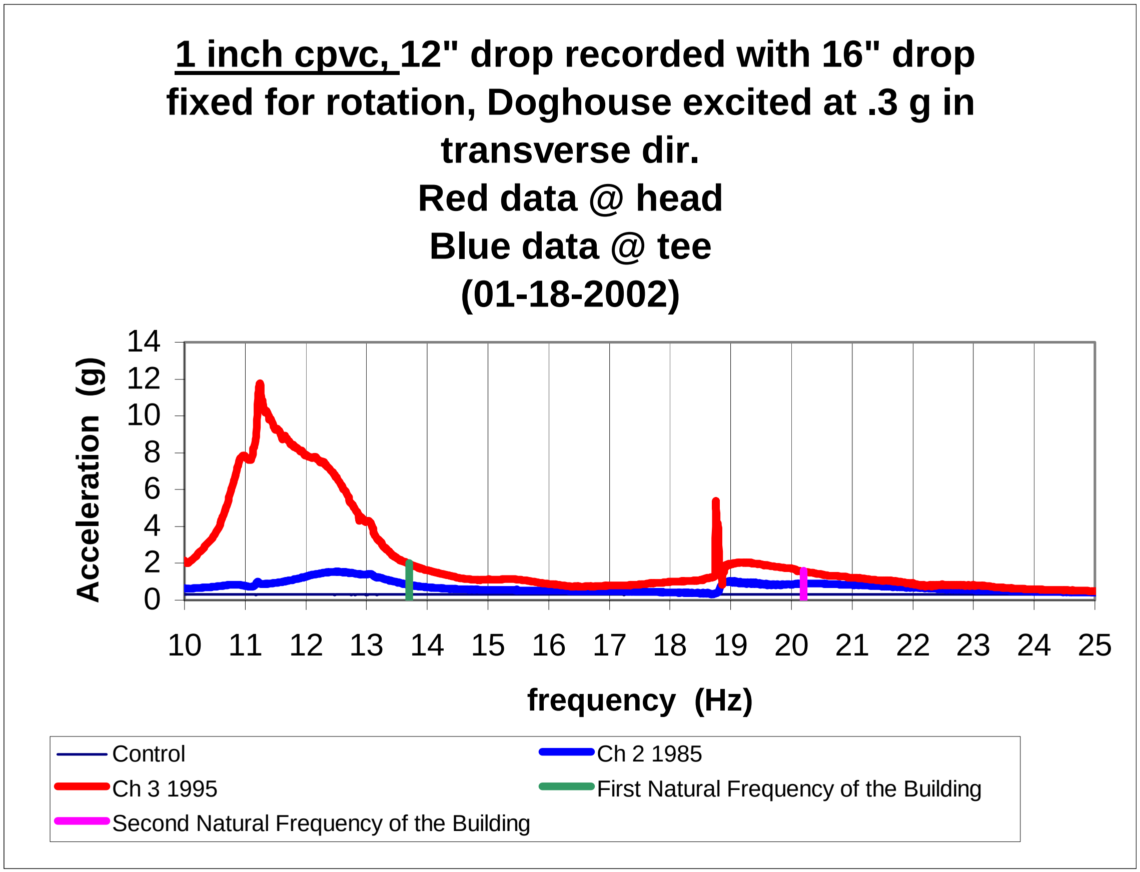


Figure 30 The Placement of the Accelerometers for Graph 17



Graph 18 Test of CPVC Sprinkler Design 3 (01-18-02)

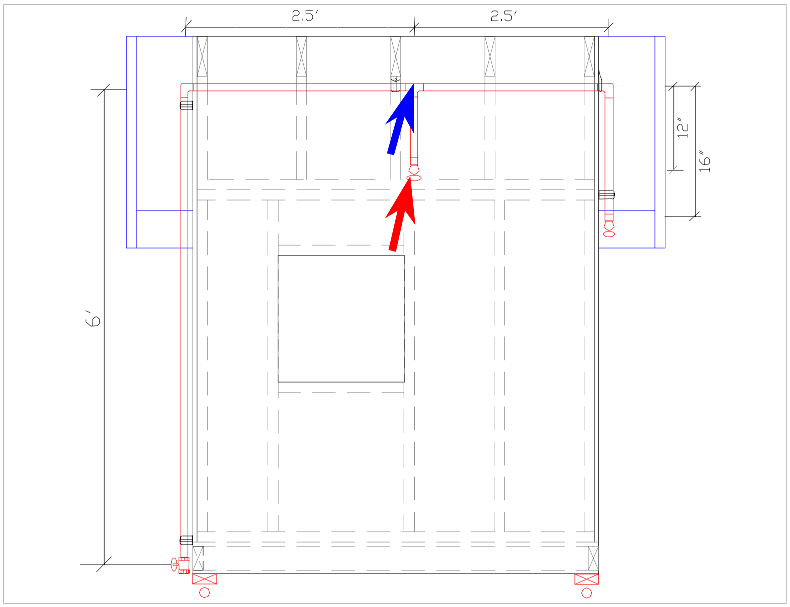
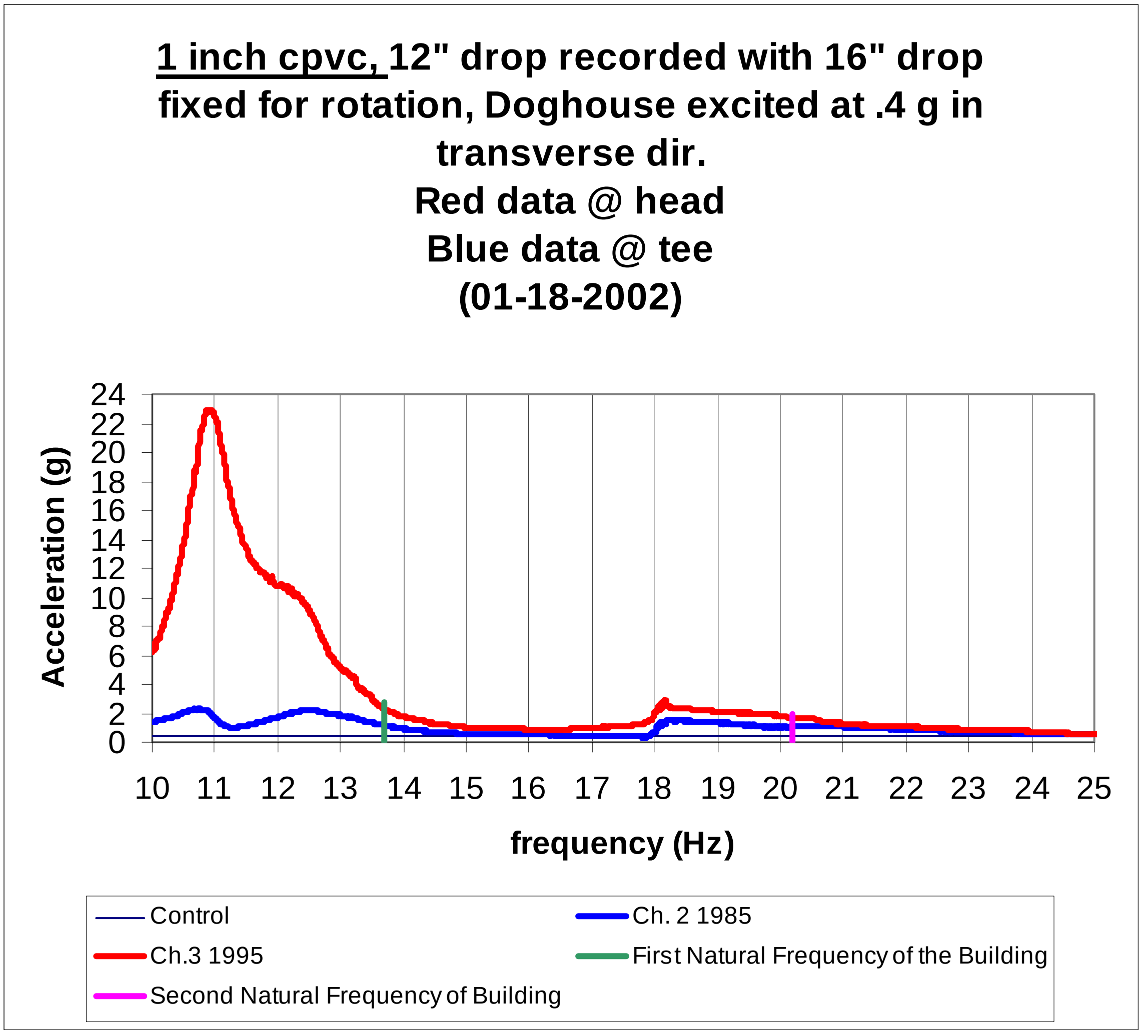


Figure 31 The Placement of the Accelerometers for Graph 18



Graph 19 Test of CPVC Sprinkler Design 3 (01-18-02)

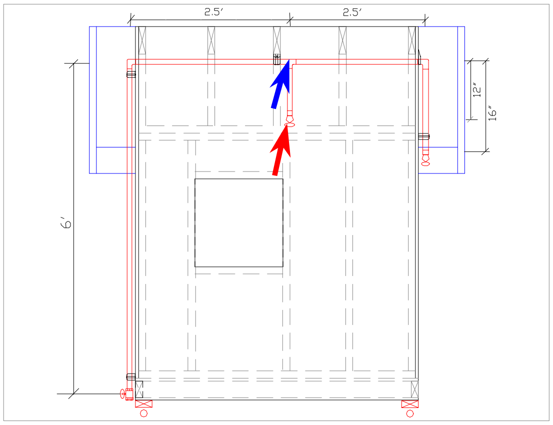
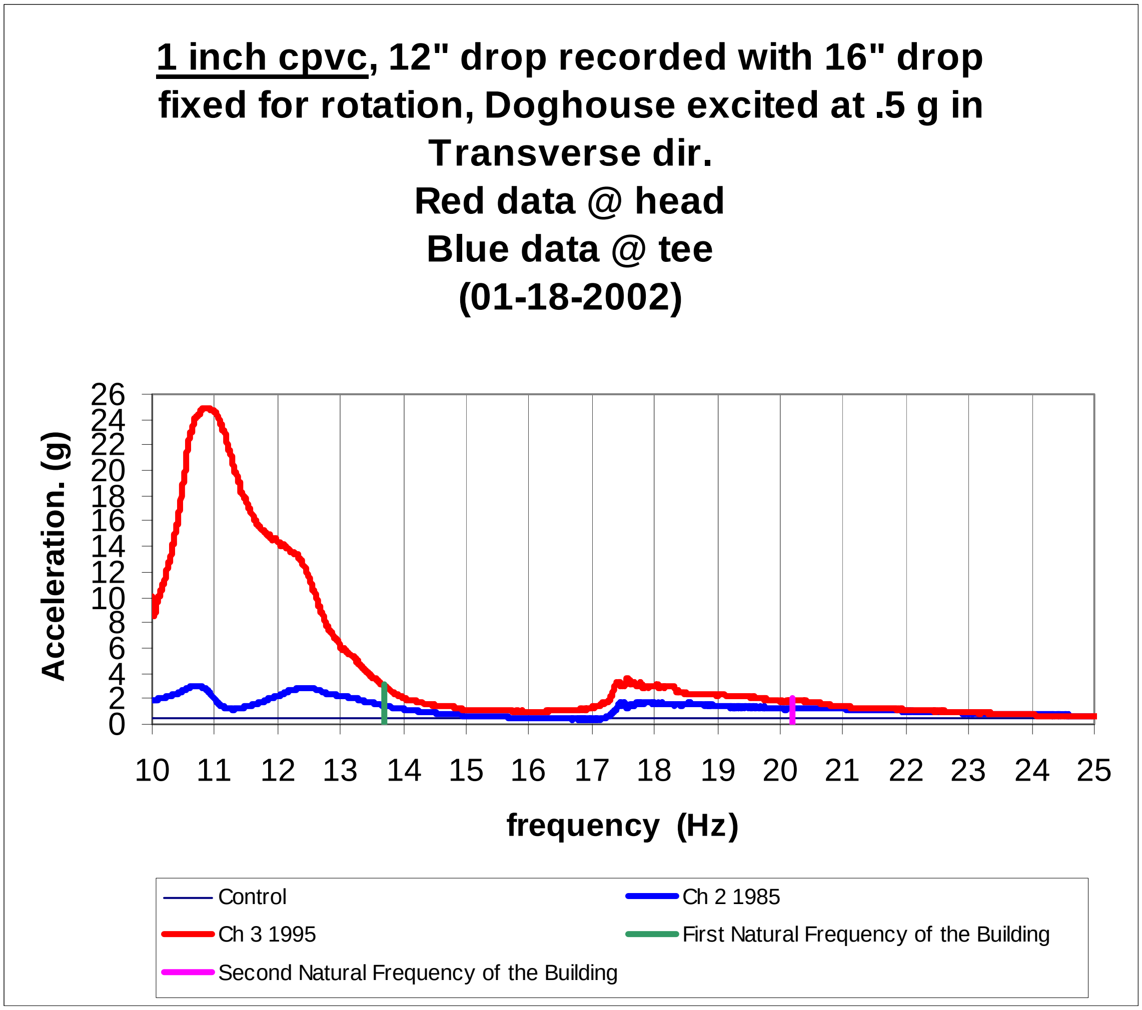


Figure 32 The Placement of Accelerometers for Graph 19



Graph 20 Test of CPVC Sprinkler Design 3 (01-18-02)

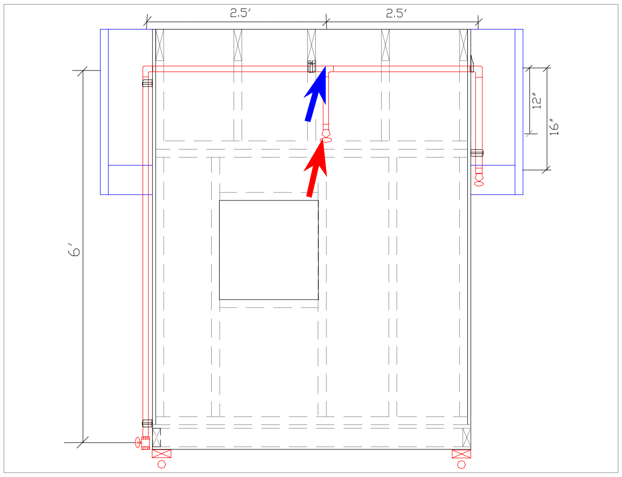


Figure 33 The Placement of the Accelerometers for Graph 20

SAP 2000 CPVC Sprinkler Design 1 Analysis

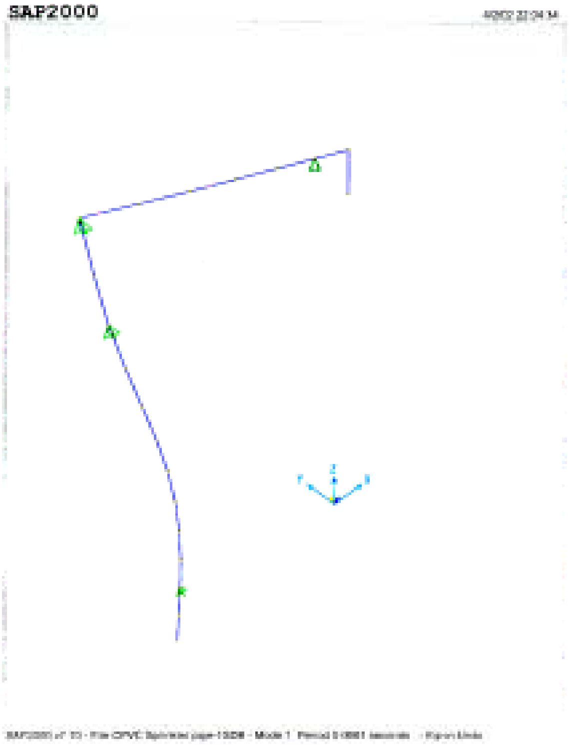
The material properties of CPVC used in the SAP2000 Analysis of all three designs are as follows:

Modulus of elasticity = 420,000 psi

Poisson's Ratio = 0.41

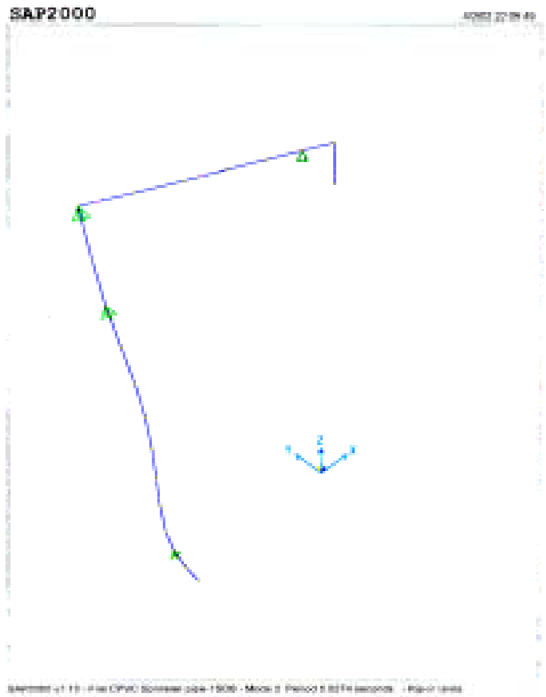
Coefficient of Thermal Expansion = 3.5 x 10^6 $^{\text{in}}/_{\text{in}}/_{\text{degree F}}$

Longitudinal Mode Shapes



Longitudinal Mode 1
Period = 0.0661 seconds
frequency = 15.1 Hz

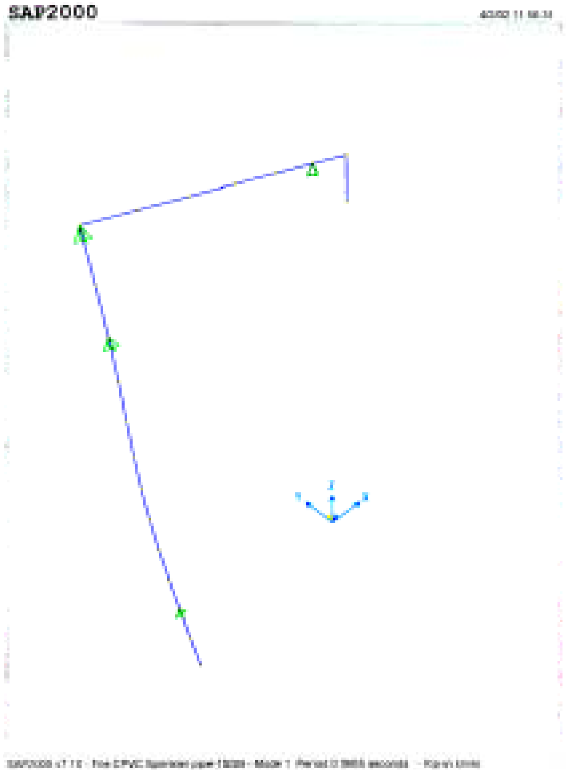
Figure 34 The First Longitudinal Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 1



Longitudinal Mode 2
Period = 0.0274 seconds
frequency = 36.5 Hz

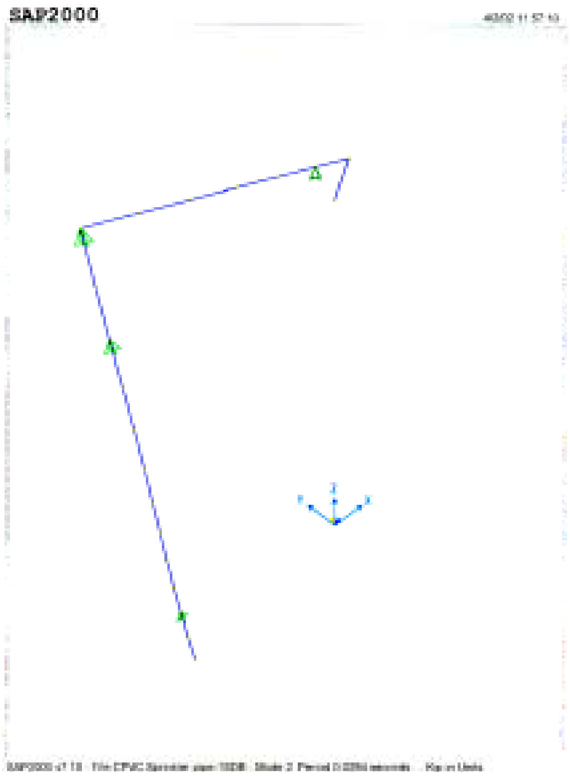
Figure 35 The Second Longitudinal Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 1

Transverse Mode Shapes



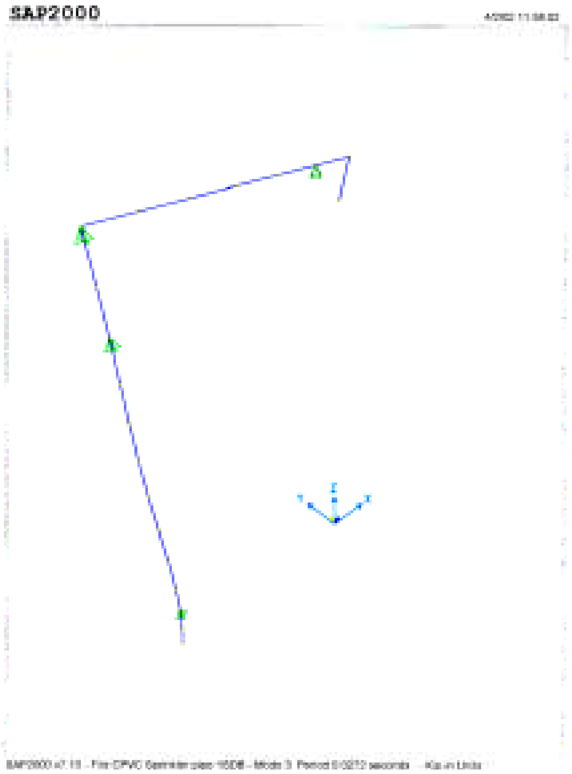
Transverse Mode 1
Period = 0.0665 seconds
frequency = 15 Hz

Figure 36 The First Transverse Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 1



Transverse Mode 2
Period = 0.0284 seconds
frequency = 35.2 Hz

Figure 37 The Second Transverse Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 1

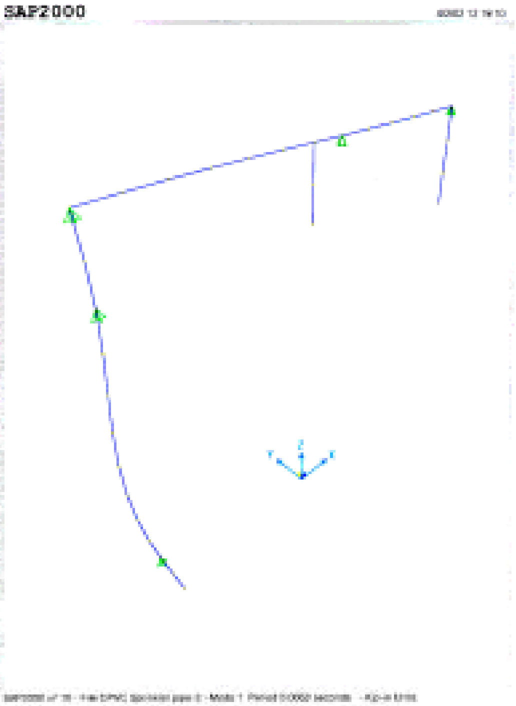


Transverse Mode 3
Period = 0.0272 seconds
frequency = 36.7 Hz

Figure 38 The Third Transverse Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 1

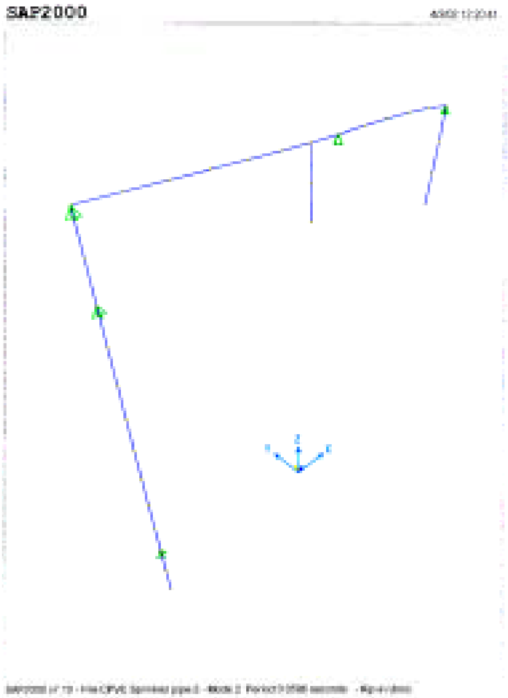
SAP 2000 CPVC Sprinkler Design 2 Analysis

Longitudinal Mode Shapes



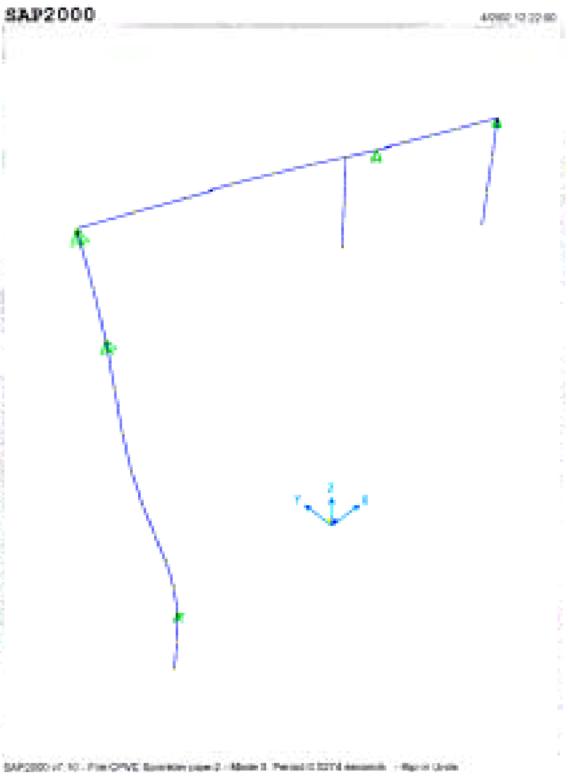
Longitudinal Mode 1
Period = 0.0662 seconds
frequency = 15.1 Hz

Figure 39 The First Longitudinal Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 2



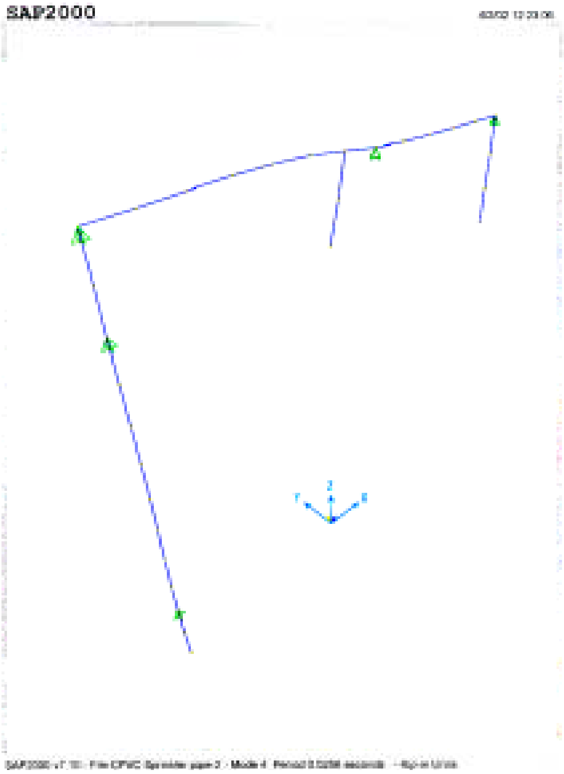
Longitudinal Mode 2
Period = 0.0596 seconds
frequency = 16.8 Hz

Figure 40 The Second Longitudinal Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 2



Longitudinal Mode 3
Period = 0.0274 seconds
frequency = 36.5 Hz

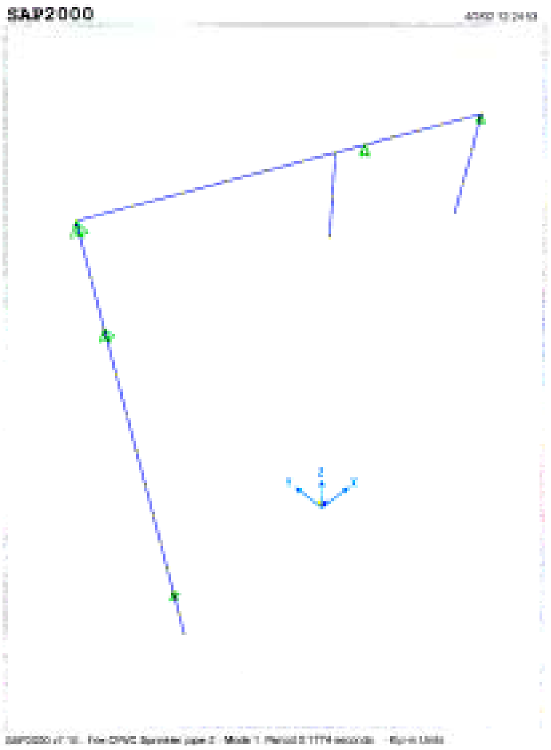
Figure 41 The Third Longitudinal Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 2



Longitudinal Mode 4
Period = 0.0256 seconds
frequency = 39 Hz

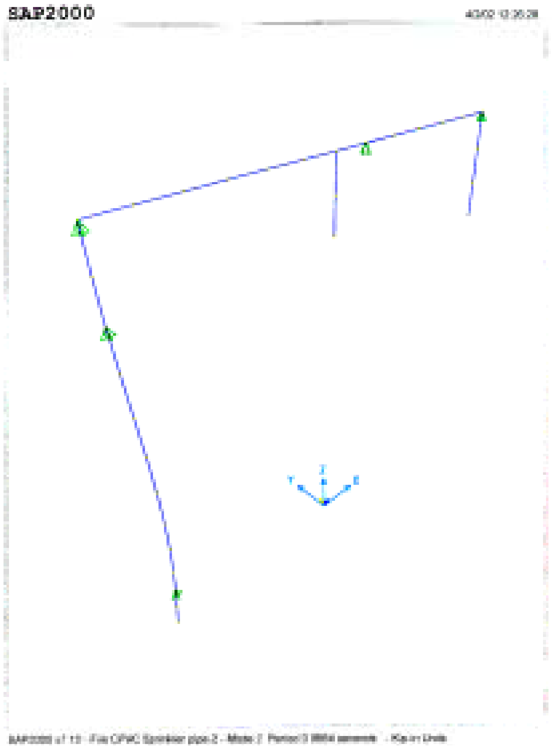
Figure 42 The Fourth Longitudinal Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 2

Transverse Mode Shapes



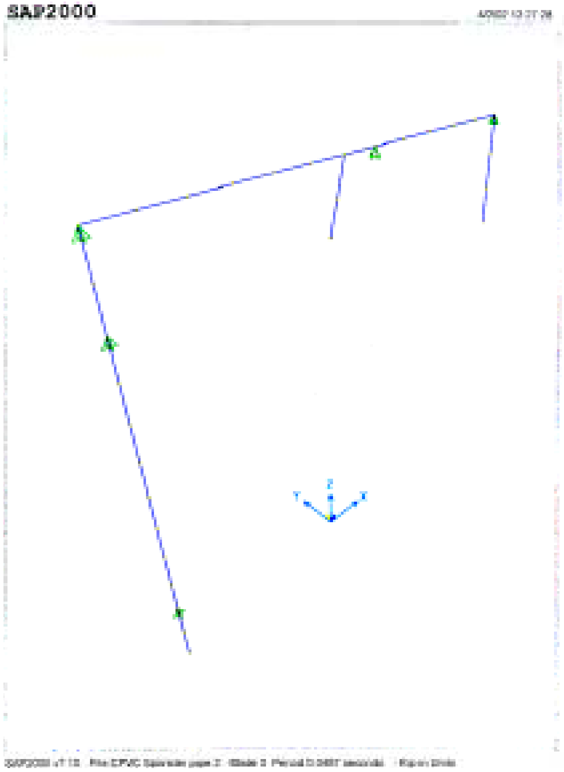
Transverse Mode 1
Period = 0.1774 seconds
frequency = 5.6 Hz

Figure 43 The First Transverse Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 2



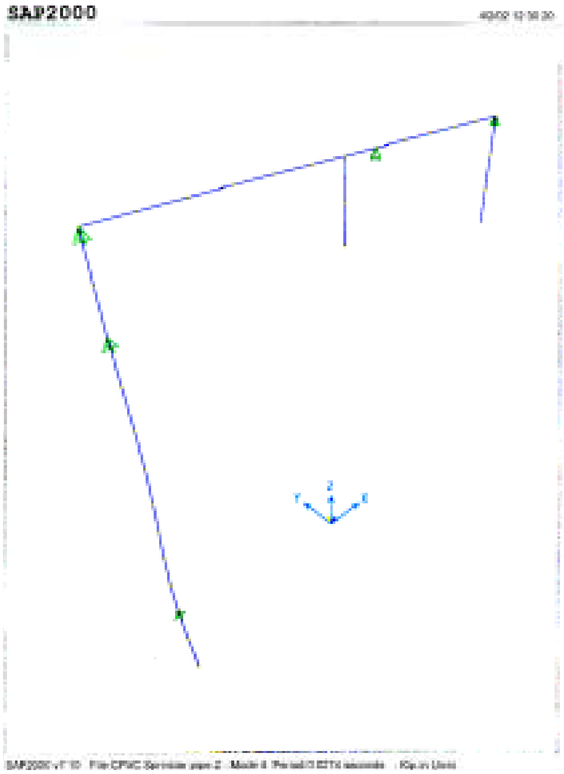
Transverse Mode 2
Period = 0.0664 seconds
frequency = 15.1 Hz

Figure 44 The Second Transverse Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 2



Transverse Mode 3
Period = 0.048 seconds
frequency = 20.5Hz

Figure 45 The Third Transverse Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 2

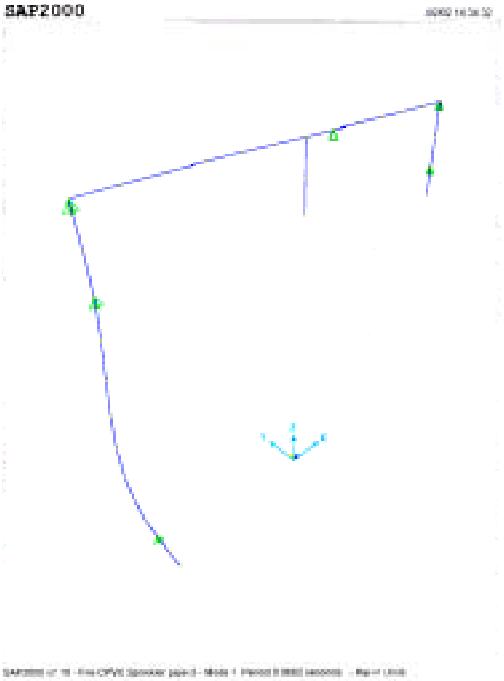


Transverse Mode 4
Period = 0.0274 seconds
frequency = 36.5 Hz

Figure 46 The Fourth Transverse Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 2

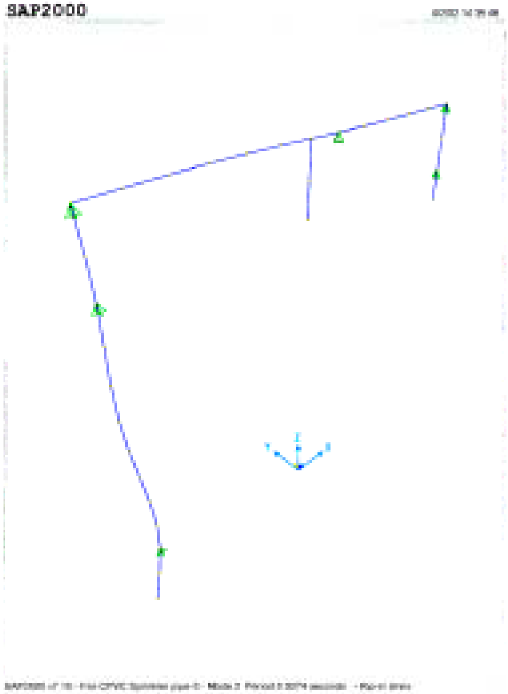
SAP 2000 CPVC Sprinkler Design 3 Analysis

Longitudinal Mode Shapes



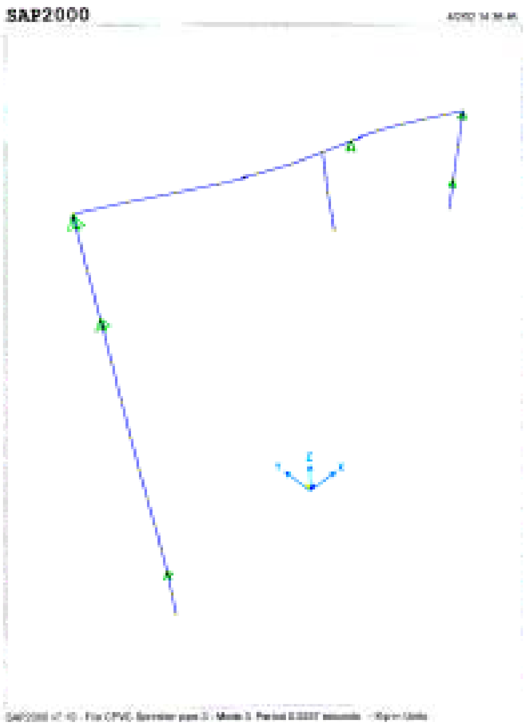
Longitudinal Mode 1
Period = 0.0662 seconds
frequency = 15.1 Hz

Figure 47 The First Longitudinal Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 3



Longitudinal Mode 2
Period = 0.0274 seconds
frequency = 36.5 Hz

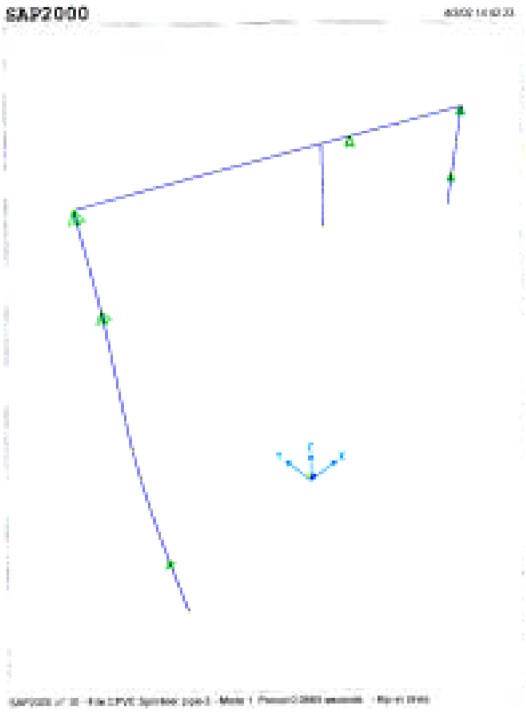
Figure 48 The Second Longitudinal Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 3



Longitudinal Mode 3
Period = 0.0257 seconds
frequency = 38.9 Hz

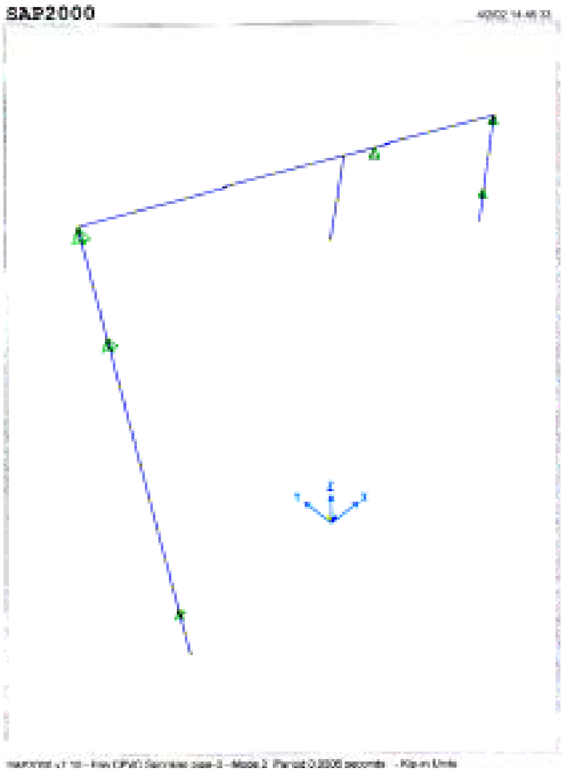
Figure 49 The Third Longitudinal Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 3

Transverse Mode Shapes



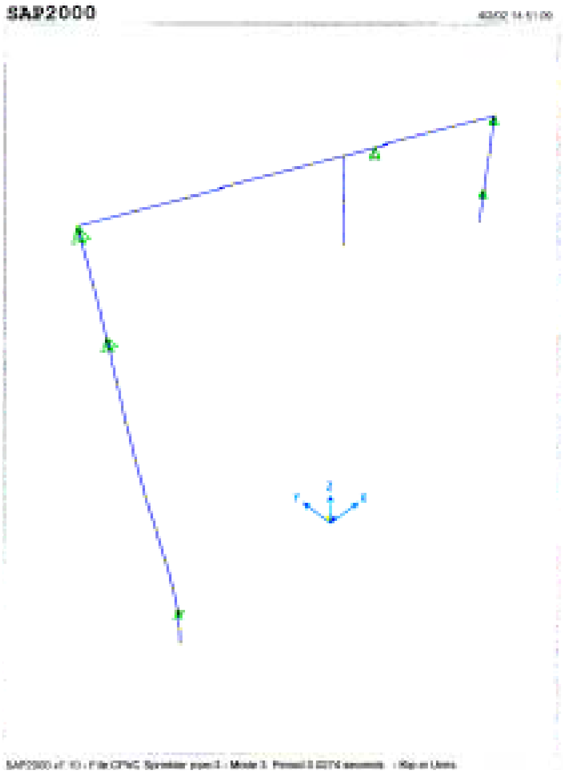
Transverse Mode 1
Period = 0.0665 seconds
frequency = 15 Hz

Figure 50 The First Transverse Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 3



Transverse Mode 2
Period = 0.0506 seconds
frequency = 19.8 Hz

Figure 51 The Second Transverse Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 3



Transverse Mode 3
Period = 0.0274 seconds
frequency = 36.5 Hz

Figure 52 The Third Transverse Mode Shape from the Sap2000 Analysis of CPVC Sprinkler Design 3

DATA REVIEW

For each of the experimental tests the building's natural frequencies are shown in all the graphs. This is to gain insight on the conditions of the sprinkler system while the building goes through its resonance periods. The placement of accelerometers was chosen to obtain acceleration data that represented the locations of the greatest expected movement in the sprinkler system. In most tests the location of the second accelerometer (blue) was attached to a fitting located close to a pipe support. In these locations the blue data closely represents the data collected from the building. When the accelerometer collecting the blue data was fixed close to a supported pipe the data collected became a base line for evaluating the amplification found between the building and the sprinkler head (blue vs. red).

Three separate CPVC sprinkler systems were tested. The first with a single drop of 6-inch, the second with both 12-inch and 16-inch drops, and the third was a modification to the supports of the second system. For the second test system the 16-inch drop was left un-braced. The support at the elbow fitting allowed the drop to rotate freely, giving the end of the system a large amount of flexibility. When the 16-inch drop was secured at the head with a pipe support the freedom of movement for that drop was removed resulting in increased amplification to the adjoining 12-inch drop.

CPVC Sprinkler Design 1

Frequencies of Sprinkler System Compared to Frequencies of the Building

Both the longitudinal and transverse testing showed that the 6-inch drop exhibited natural frequencies similar to the building's natural frequency. There was a second observed longitudinal natural frequency of the sprinkler system that the building did not share.

Floor Acceleration vs. Acceleration at the Head

The base accelerations used were 0.4g in the longitudinal direction and 0.2g when the model was tested in the transverse direction. The maximum acceleration when tested in the longitudinal direction with a base acceleration of 0.4g observed at the head was 8g. Testing in the transverse direction with a base acceleration of 0.2g yielded maximum-recorded acceleration of 3g at the head. Since test data from the second accelerometer (blue data) records from a joint of the sprinkler system that's fixed securely to the ridge board, the amplification observed closely represents the models own amplification.

Amplification Observed

The amplification of the acceleration at the base to the accelerations recorded at the head was from 15 to 20 times. The acceleration at the head records the maximum amplification of the sprinkler system as its being driven by the acceleration from the top of the building. The amplification of the sprinkler drop over the input acceleration from the building in both the test directions is about 3 times.

Frequencies of the Test Design Compared to the SAP2000 Results

The SAP2000 program identified a longitudinal and transverse first mode shape around 15Hz. Test data showed that under longitudinal shaking the only observed mode shape centered about 15Hz. The buildings first longitudinal mode shape is also around 15Hz and this created increased amplification in the accelerations of the sprinkler system. At 15Hz excitement in the transverse direction the 6-inch did not show a peak in amplification even though it was excited. The influence of the building shaking during testing makes it difficult to pick out any independent sprinkler mode shapes. SAP2000 analysis predicted modal frequencies outside of the test range and are included in the data to show there are expected mode shapes in the high frequency range.

CPVC Sprinkler Design 2

Frequencies of Sprinkler System Compared to Frequencies of the Building

This CPVC design included a large degree of flexibility from the lack of rotational restraints. The system was free to rotate from the elbow connection at the back of the building to the end of the last drop. Therefore test results from the 16-inch drop at the sprinkler head exhibited no response from the buildings amplification. The acceleration data from the elbow of the 16-inch drop peaked at similar natural frequencies to the building. The data collected at the head of the 16-inch drop showed one exhibited natural frequency of about 10 Hz in the longitudinal plane and about 11.5 in the transverse plane. The data from head and tee fitting of the 12-inch drop showed the natural frequencies of the sprinkler section were similar to the buildings at 12 and 19.5Hz in the transverse direction and 15.4Hz in the longitudinal direction.

Floor Acceleration vs. Acceleration at the Head

The base accelerations used was 0.4g in both directions of testing. The maximum acceleration found from the test in the longitudinal direction was observed at the head of the 12-inch drop at 12g. Testing in the transverse direction yielded a maximum acceleration of 8g at the head of the 12-inch drop. When the 16-inch drop was tested the accelerations recorded at the head exhibited independent natural frequencies to the remaining parts of the model. That drops flexibility allowed the particular section of the sprinkler system to have a higher natural period than the rest of the model. The recorded acceleration from the elbow (blue data) of the 16-inch drop displayed similar natural frequencies to the building in both planes of testing. The flexibility of the 16-inch CPVC pipe between the elbow and the head acted to dampen any input accelerations from the rest of the model to the sprinkler head. The recorded acceleration values for the 16-inch drop are much less than those observed at the 12-inch drop. The recorded acceleration of the sprinkler head at the end of the 16-inch drop was 6.5 and 3.5g in the longitudinal and transverse shake planes respectively.

During Transverse testing it was noted that the 12-inch drop exhibited a strong vertical mode shape during the second natural frequency of the system. The test represented by Graph 15 displays that vertical acceleration data experienced at the drop, figure 25 shows the location of the accelerometers on the model. Acceleration values were greatest at the tee fitting. This second mode shape caused the suspended CPVC line to experience torsion resulting a vertical acceleration of 4.5g at the tee.

Amplification Observed

The amplification of the acceleration at the base to the accelerations recorded at the head of the 12-inch drop was from 20 times for longitudinal and 30 times for the transverse recording. The amplification observed at the 16-inch drop was 15 times in the longitudinal test and 9 times in the transverse test. The amplification of the 12-inch sprinkler drop over the input acceleration from the building in both the test directions is about 3 times. The amplification of the 16-inch drop during longitudinal testing is independent of the buildings natural frequency. The amplification of 15 times that of the base input is due to the physical properties of the CPVC drop itself. The amplification in the 16-inch drop at 9 times during transverse testing is also independent from the amplification of the building.

Frequencies of the Test Design Compared to the SAP2000 Results

For this design SAP2000 predicted mode shapes for the sprinkler system that resembled the buildings natural frequencies. This sprinkler model was amplified at the frequencies identified in the SAP2000 Analysis, except at the 16-inch drop. Due to the flexibility, the 16-inch drop exhibited mode shapes independent from the rest of the model and not identified by the SAP2000 analysis. SAP2000 analysis predicted modal frequencies outside of the test range and are included in the data to show there are expected mode shapes before and after the test frequency range.

CPVC Sprinkler Design 3

This design fixes the 16-inch drop to the building but in all other ways is identical to the previous model set-up.

Frequencies of Sprinkler System Compared to Frequencies of the Building

By fixing the 16-inch drop the stiffness of the sprinkler system was increased. The observed natural frequencies from both drops now showed similarities to the natural frequencies of the entire sprinkler line. The natural frequencies of the 12-inch drop remained the same as system design 2, while the natural frequencies of the 16-inch drop changed to resemble those similar to the buildings.

Floor Acceleration vs. Acceleration at the Head

The base acceleration was 0.4g in the longitudinal direction of testing. The maximum acceleration of the 12-inch drop when tested in the longitudinal direction was

13g. The maximum acceleration of the 16-inch drop when tested in the longitudinal direction was 3g at the head and 5g at the elbow. The higher acceleration observed at the elbow is due to the u-shaped support that allowed a greater freedom of movement than did the clamp support used to attach the remainder of the sprinkler system.

The base acceleration at testing in the transverse direction yielded a maximum-recorded acceleration of 12g with a base input of 0.3g, 23g with a base input of 0.4g, 25g with a base input of 0.5g at the head of the 12-inch drop. The goal of changing the base input was to see how the percent of amplification at the sprinkler head changed from incremental increases. The 16-inch drop was tested in the transverse direction at 0.4g and yielded a max acceleration value of 4g during the frequency range where both the building and the sprinkler system were experiencing resonance.

The recorded acceleration values from the 16-inch drop are much less than those observed from the 12-inch drop. With the 12-inch drop left as the only section of the sprinkler system able to rotate freely in the transverse direction its acceleration at the drop was magnified twice as much as the previous recordings when the 16-inch drop was free to rotate. The recorded acceleration of the sprinkler head at the end of the 16-inch drop was just 6.5 and 3.5g in the longitudinal and transverse shake planes respectively.

Amplification Observed

The transverse recording of the 12-inch drop yielded the largest observed acceleration amplification of all tests. To finish the testing of CPVC sprinkler system 3 three tests of the 12-inch drop were run in the transverse direction to get a range of amplification over a range of base input acceleration values. The last three base acceleration inputs tested were 0.3, 0.4, and 0.5g. The change in amplification of the 12-

inch drop during the three different base input levels was greatest when the base acceleration increased to 0.4g from 0.3g. At that change the amplification from the base to the sprinkler head increased from 40 times to 63 times When the model was then tested at 0.5g the amplification at the sprinkler head dropped to 54 times.

The amplification of the 16-inch drop was 10 times at the head and 12.5 times at the elbow when tested in the longitudinal direction. The amplification at the elbow was higher than that from the head due to the location of the clamp near the head and the fact that the u-shaped support at the elbow was only restraining the pipe in the vertical direction. The elbow ended up being less stiff than the sprinkler head. When the 16-inch drop was tested in the transverse direction the overall increased stiffness caused the elbow to react with significant amplification during both the building natural frequencies At the other end the head exhibited signs of significant amplification only at a frequency slightly before the buildings first natural frequency.

Frequencies of the Test Design Compared to the SAP2000 Results

Little change occurred in the expected modal frequencies when the SAP2000 analysis of CPVC Sprinkler Design 2 was modified to become CPVC Sprinkler Design 3. Confirmed by the test results showing the change from CPVC Design 2 to 3 induced no change in modal frequencies. SAP2000 analysis predicted modal frequencies outside of the test range and are included in the data to show there are expected mode shapes before and after the test frequency range. The computer analysis results identified all the first modal frequencies recorded during CPVC testing, as well as the second transverse mode shapes from designs two and three. The test range for data collection was only from 10-25 Hz.

RESULTS FROM CPVC SPRINKLER SYSTEM TESTING

Table 2 Tabulated Results From CPVC Sprinkler Testing

Test Direction	Design	Recording Location	Excited Freq. Ranges (Hz)	Highest Amplification	SAP2000 Fundamental Frequencies (Hz)
Longitudinal	CPVC 1	6” drop	15-17, 18-22	22 x	15.1, 36.5
	CPVC 2	12” drop	15-17, 19-22	30 x	15.1, 16.8, 36.5, 39
		16” drop	9-11, 15-17, 20-22	16 x	
	CPVC 3	12” drop	15-17, 20-22	30 x	15.1, 36.5, 38.9
		16” drop	15-17	13 x	
Transverse	CPVC 1	6” drop	13-14, 19-22	15 x	15, 35.2 36.7
	CPVC 2	12” drop	11-14, 18-23	20 x	5.6, 15.1, 20.5, 36.5
		16” drop	11-14, 18-23	9 x	
	CPVC3	12” drop	10-13, 18-23	58 x	15, 19.8, 36.5
		16” drop	10-13, 18-23	10 x	
Vertical		12” drop	10-13, 18-23	11 x	---------------------

The frequency testing range that gave clean acceleration recordings was from about 9 Hz to just past 30Hz. Defined mode shapes were observed within the frequency sweep from 10 Hz to 25 Hz. In the transverse shaking direction the designs showed signs of an early and late mode shapes however this erratic data could not be used to define a mode natural frequency. The purpose of mentioning any mode shapes outside the tested range is because the three SAP 2000 analyses' identifies modal frequencies both before and after the test range. The displayed natural frequencies from the three SAP2000 computer models identified in the test range are close to identical to the mode shapes observed in testing. Any acceleration data collected before or after this sweep range appeared as erratic. Erratic data is labeled as noise because no sense can be made of it.

By testing both ends of the sprinkler drops a good reference was made between the acceleration delivered from the building and the additional acceleration developed at the end of the hanging drop. The blue data from pipe sections securely fixed to the model served as a baseline to compare the accelerations coming from the building to the amplified accelerations in the sprinkler heads.

The computer models of the three test set-ups generated results that closely mirrored the modal frequencies found from testing. In many of the test cases the amplification observed at the sprinkler head was closely associated with the driving frequency of the building itself.

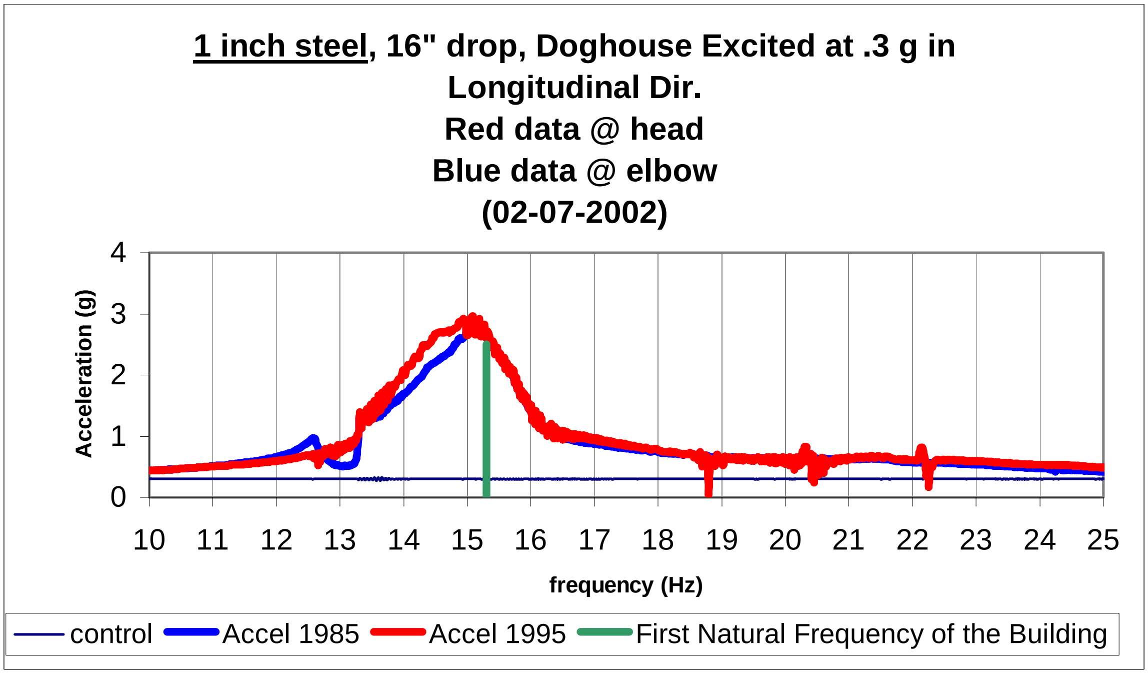
No failures of any kind occurred during the CPVC sprinkler tests.

8 DYNAMIC PROPERTIES OF STEEL SPRINKLERS

DESCRIPTION OF TEST SET-UPS

The tested design involved bringing the sprinkler line up the back of the model through the opening under the eve and into the inside. The set-up had a 12-inch drop plumbed in the middle of the model's interior and a 16-inch drop extending out the other side and down the front gable. The following data was recorded at both ends of fire system’s drops.

LONGITUDINAL DATA



Graph 21 Test of Steel Sprinkler Design (02-07-02)

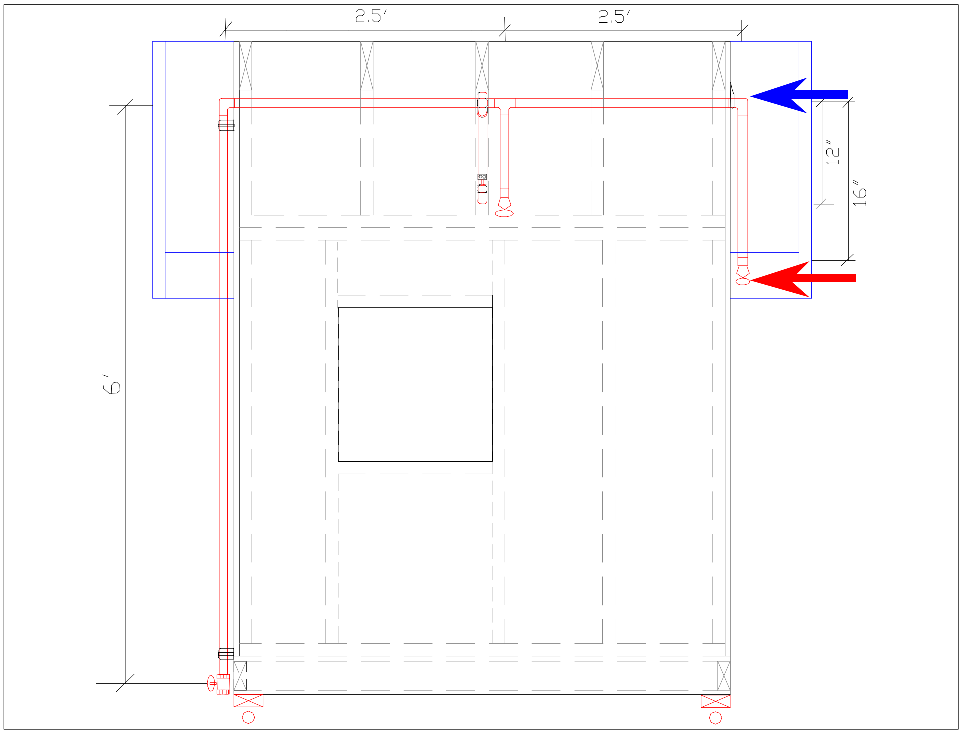
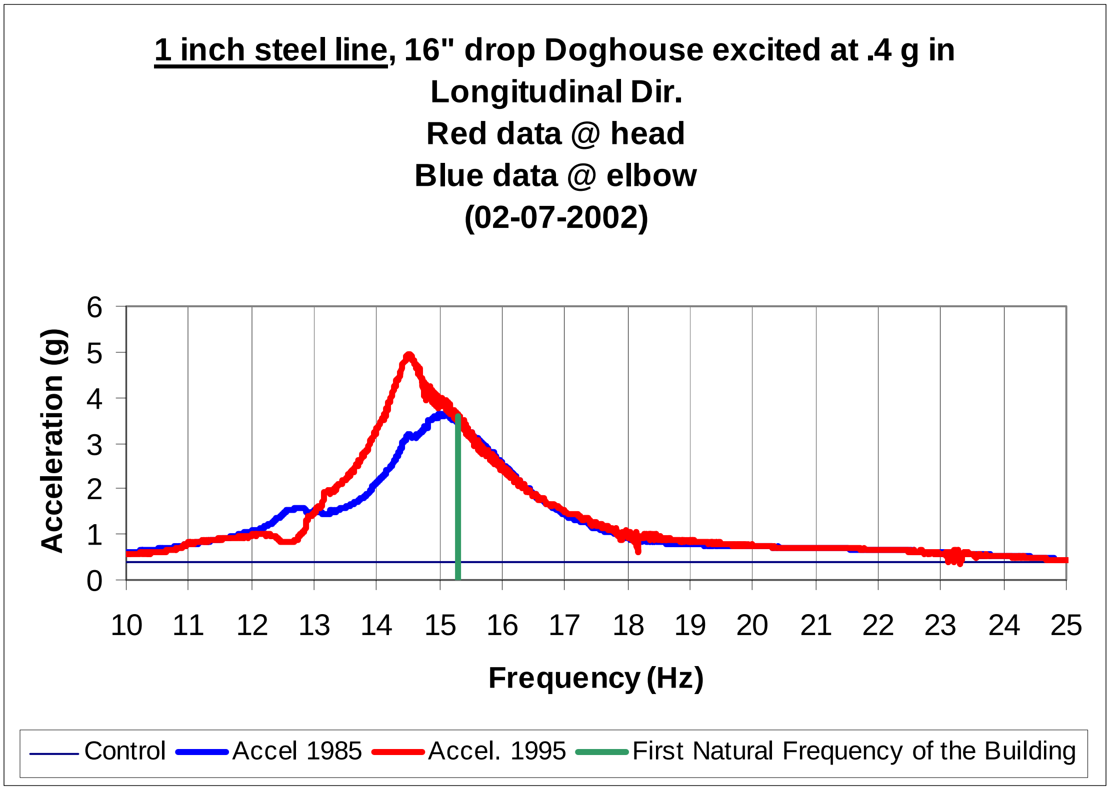


Figure 53 The Placement of the Accelerometers for Graph 21



Graph 22 Test of Steel Sprinkler Design (02-07-02)

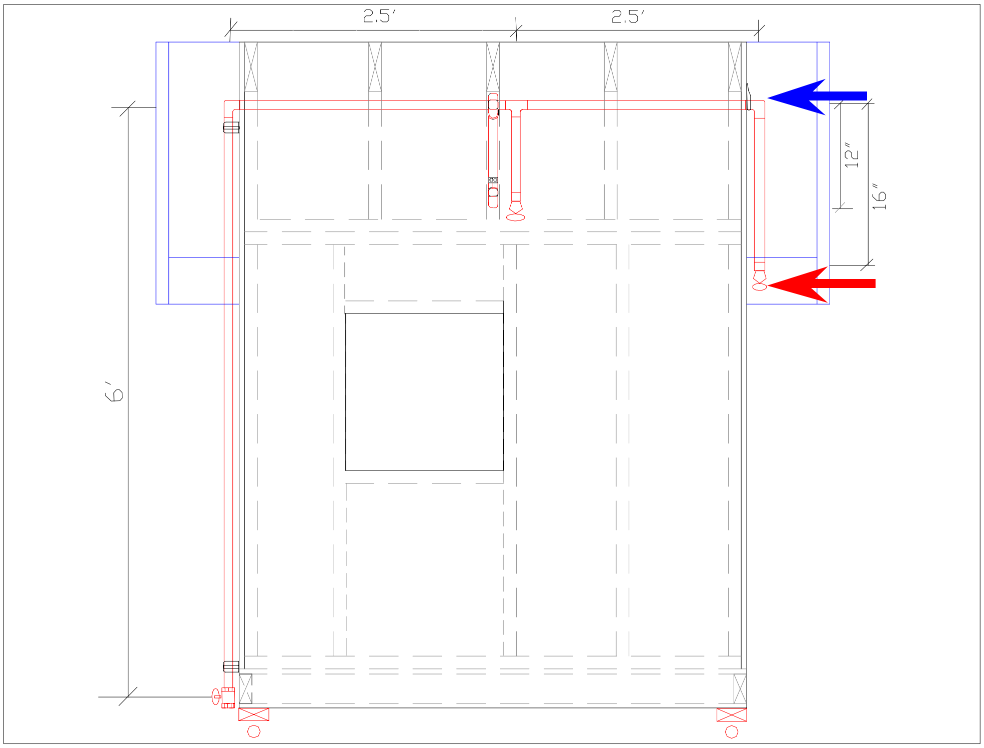
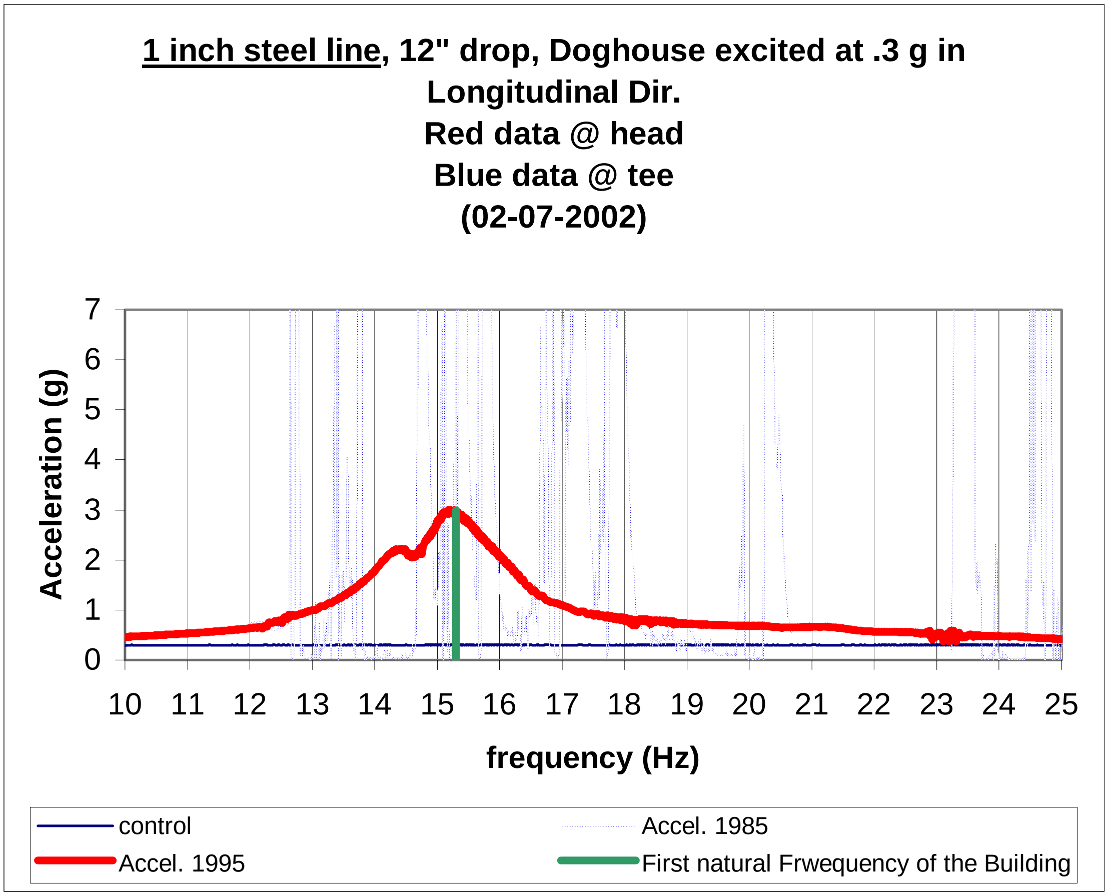


Figure 54 The Placement of the Accelerometers for Graph 22



Graph 23 Test of Steel Sprinkler Design (02-07-02)

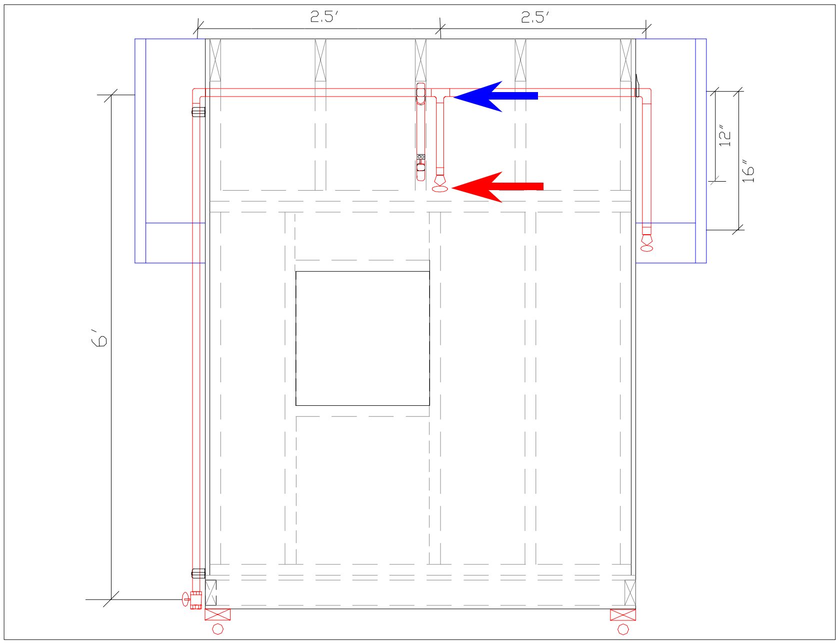
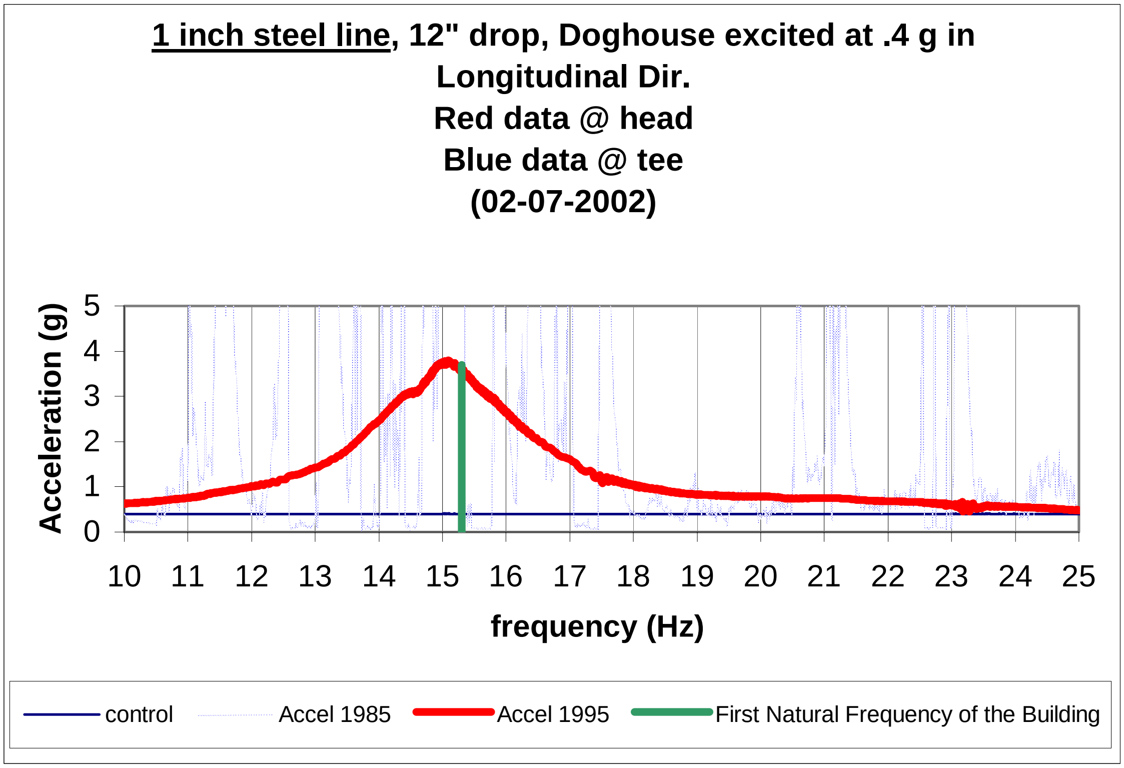


Figure 55 The Placement of the Accelerometers for Graph 23



Graph 24 Test of Steel Sprinkler Design (02-07-02)

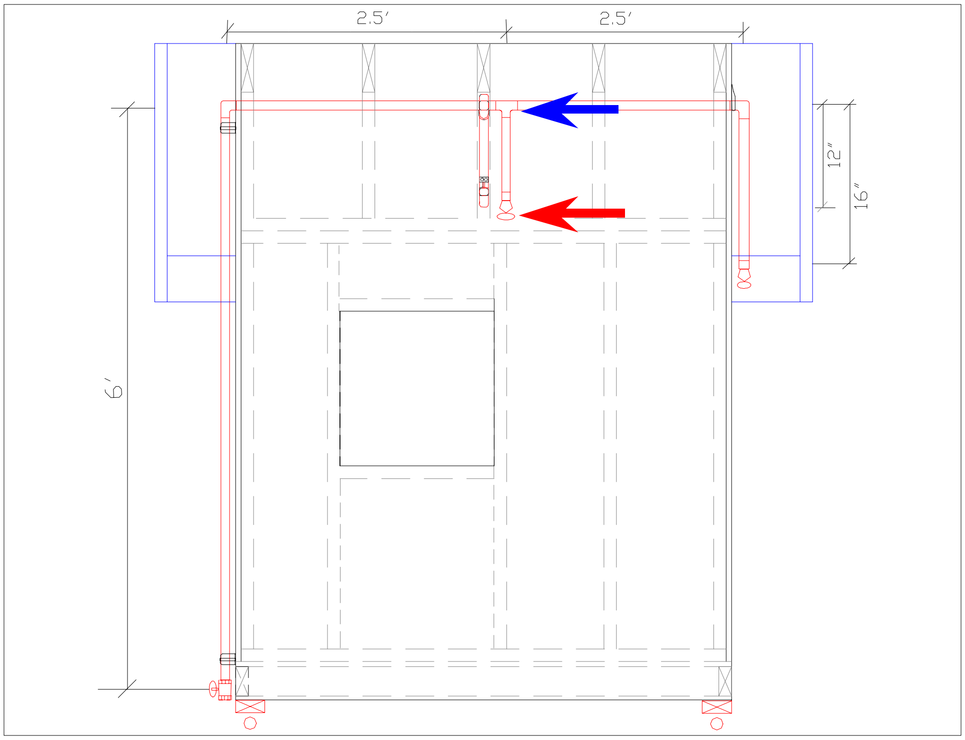
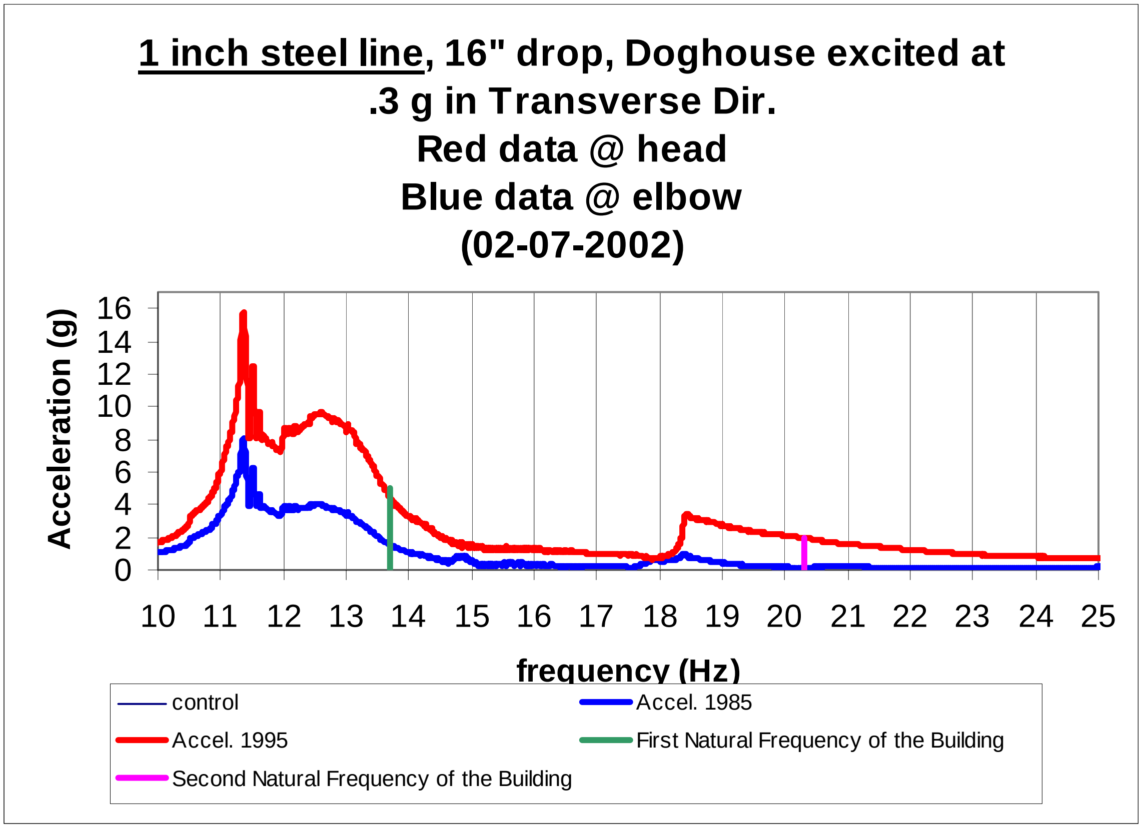


Figure 56 The Placement of the Accelerometers for Graph 24

TRANSVERSE DATA



Graph 25 Test of Steel Sprinkler Design (02-07-02)

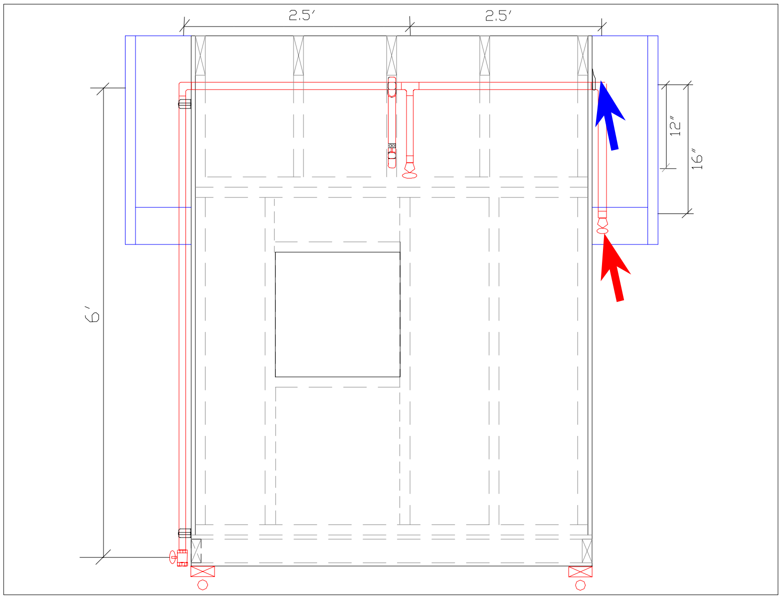
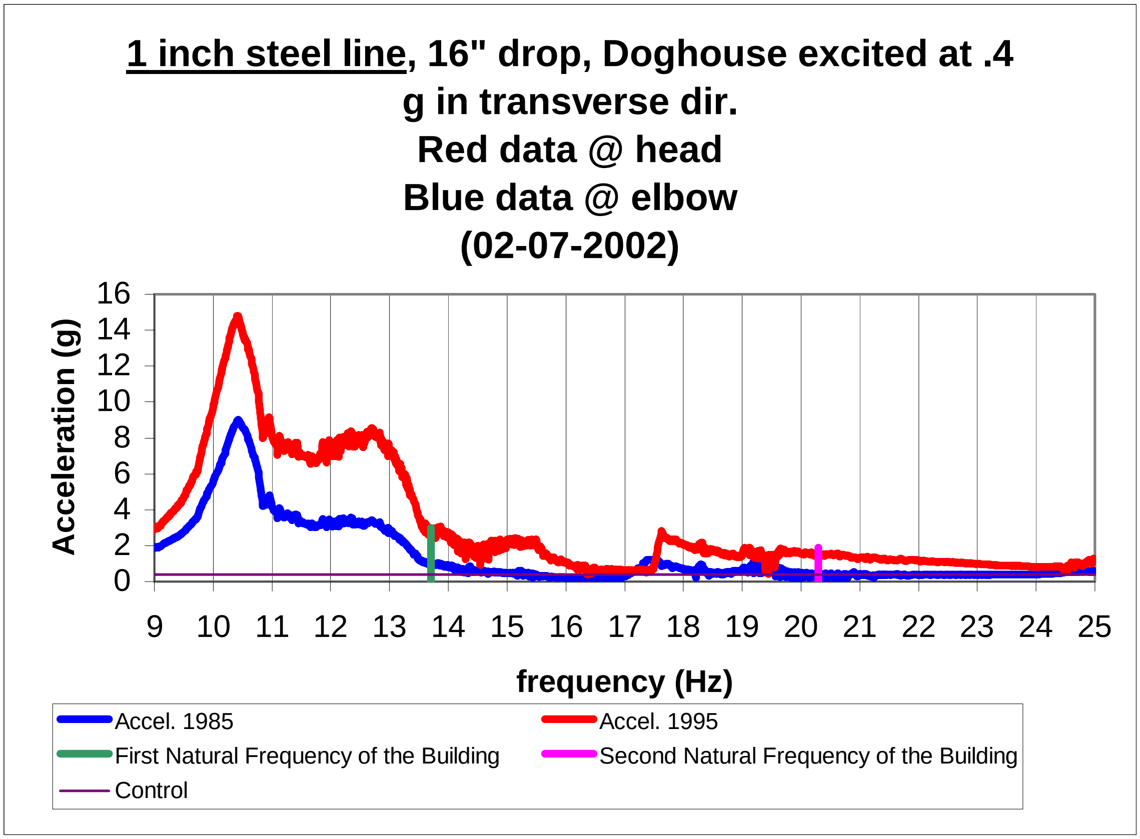


Figure 57 The Placement of the Accelerometers for graph 25



Graph 26 Test of Steel Sprinkler Design (02-07-02)

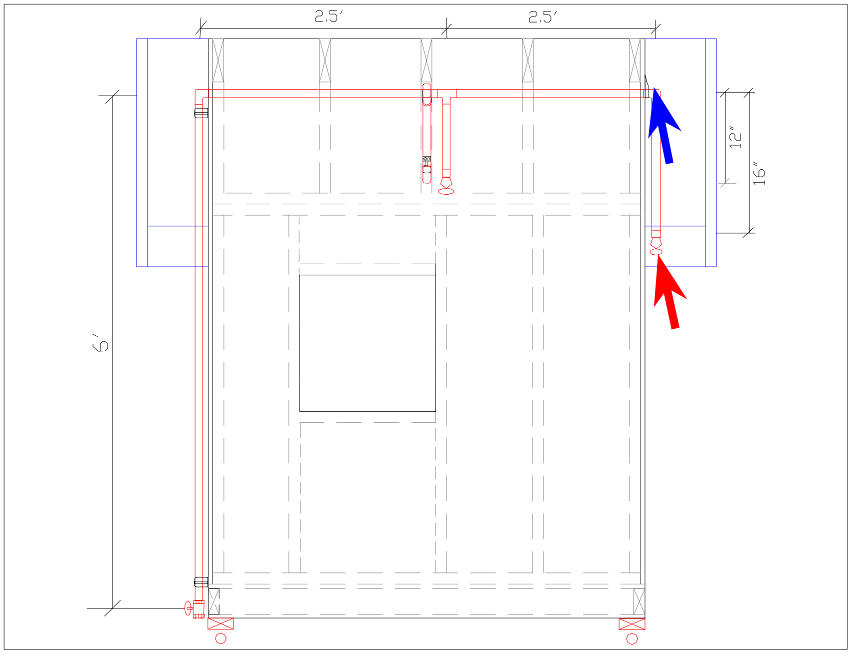
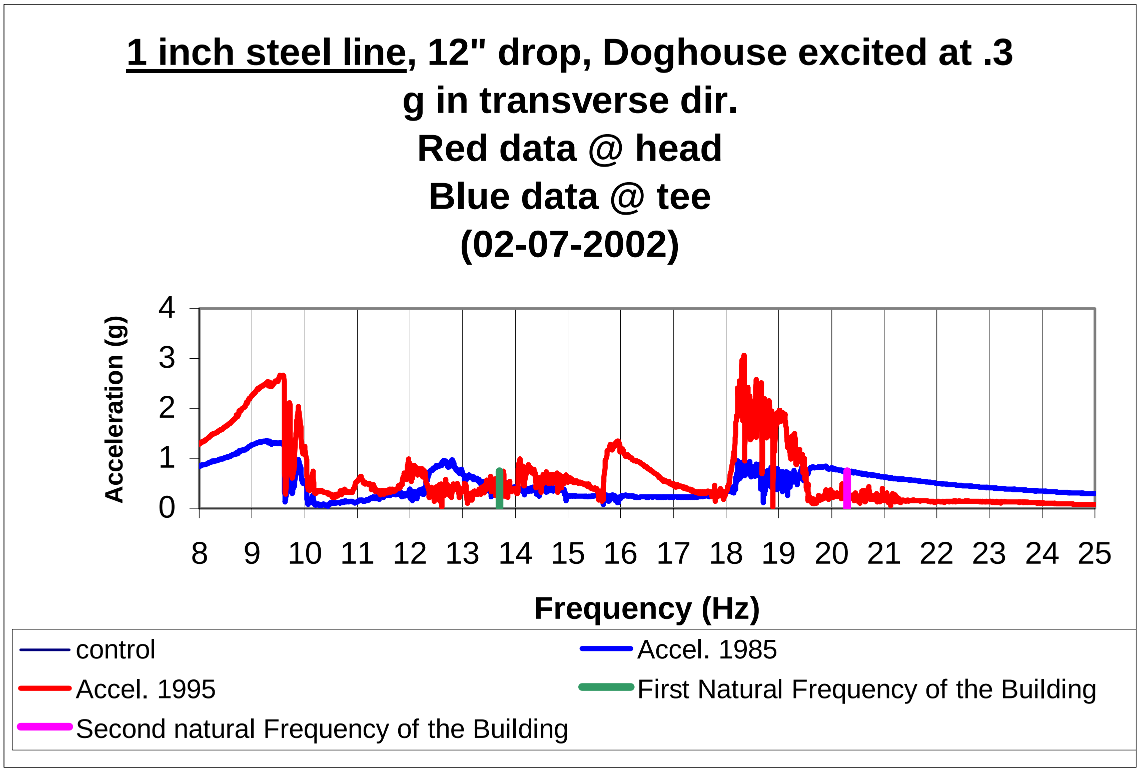


Figure 58 The Placement of the Accelerometers for Graph 26



Graph 27 Test of Steel Sprinkler Design (02-07-02)

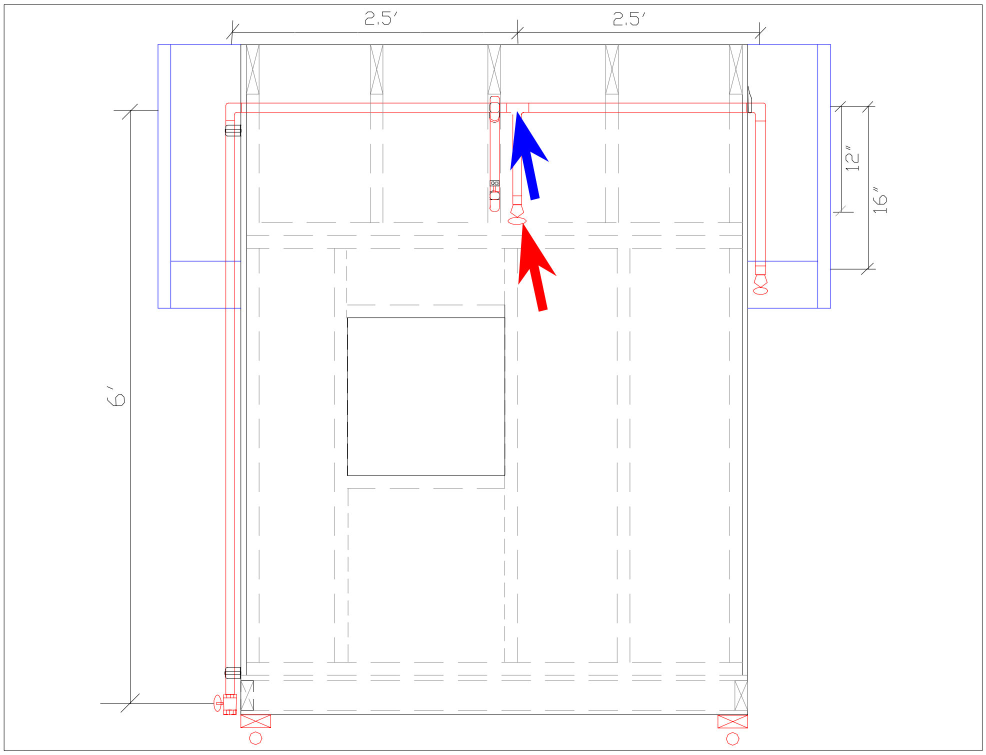
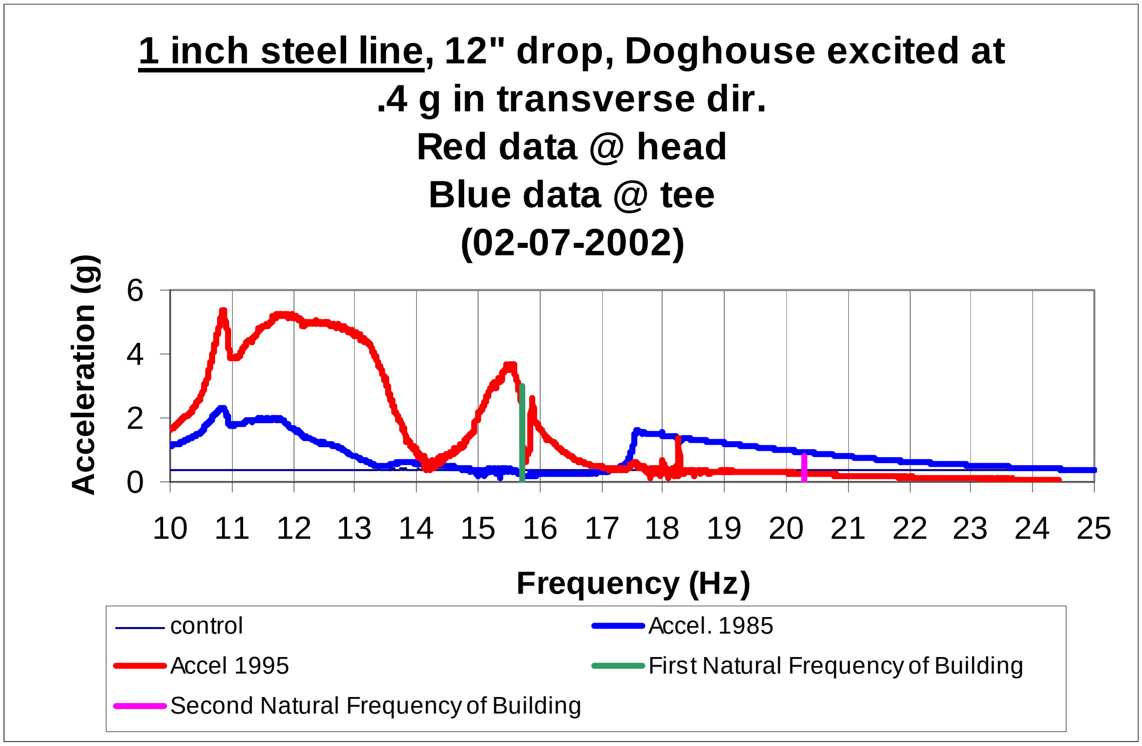


Figure 59 The Placement of the Accelerometers for Graph 27



Graph 28 Test of Steel Sprinkler Design (02-07-02)

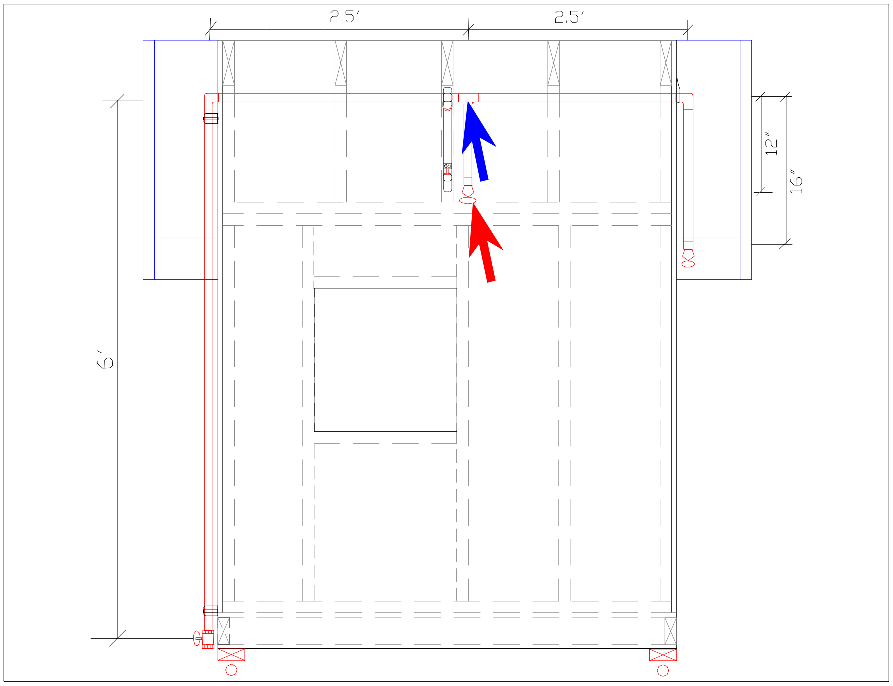
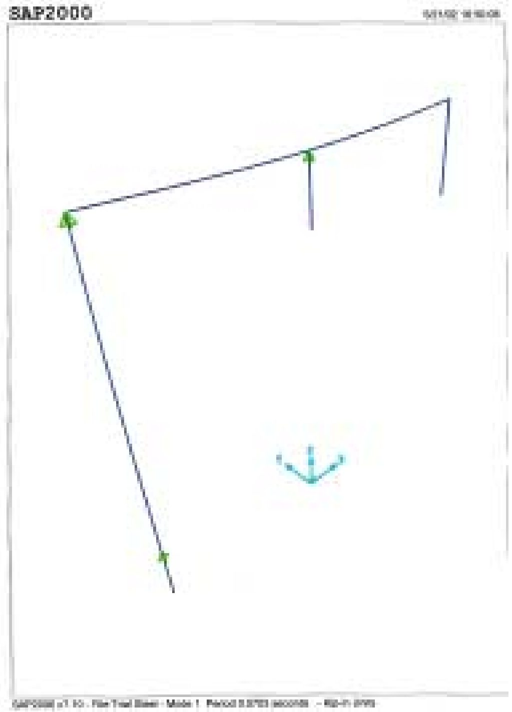


Figure 60 The Placement of the Accelerometers for Graph 28

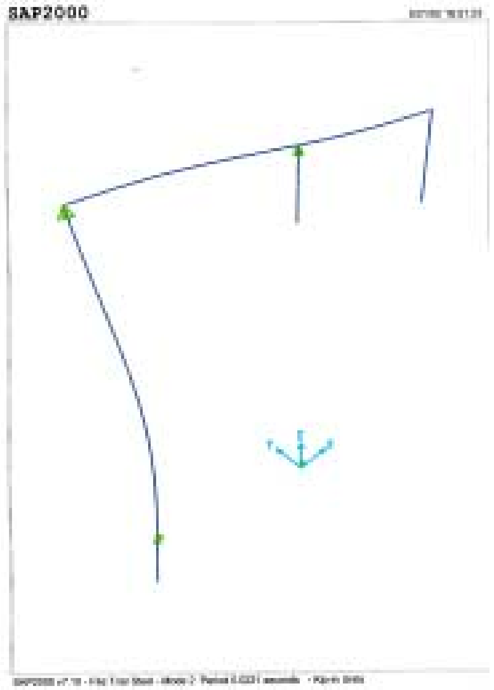
SAP2000 Steel Sprinkler System Analysis

Longitudinal Mode Shapes



Longitudinal Mode 1
Period = 0.0703 seconds
frequency = 14.2 Hz

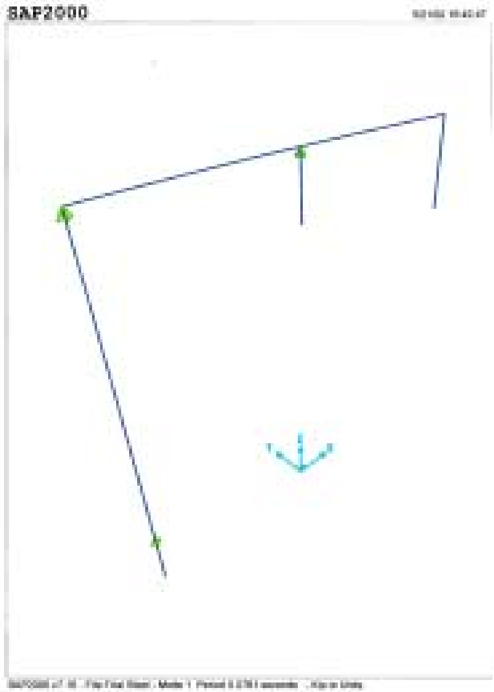
Figure 61The First Longitudinal Mode Shape from the SAP2000 Analysis of Steel Sprinkler Design



Longitudinal Mode 2
Period = 0.0221 seconds
frequency = 45.2 Hz

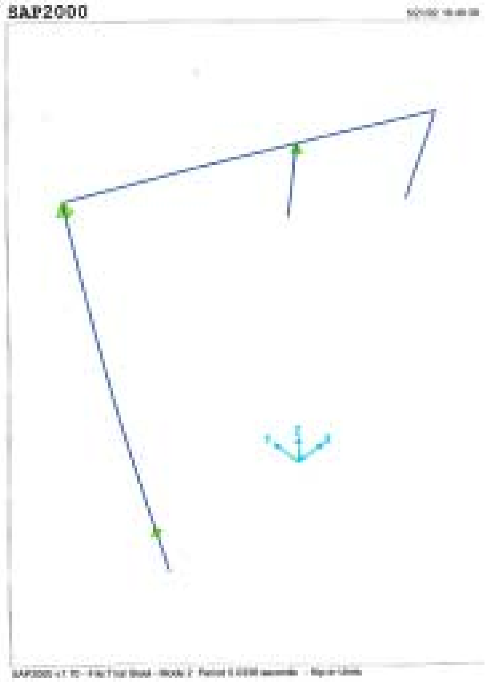
Figure 62 The Second Longitudinal Mode Shape from the SAP2000 Analysis of Steel Sprinkler Design

Transverse Mode Shapes



Transverse Mode 1
Period = 0.0761 seconds
frequency = 13.1 Hz

Figure 63 The First Transverse Mode Shape from the SAP2000 Analysis of Steel Sprinkler Design



Transverse Mode 2
Period = 0.0336 seconds
frequency = 29.8 Hz

Figure 64 The Second Transverse Mode Shape from the SAP2000 Analysis of Steel Sprinkler Design

DATA REVIEW

Frequencies of Sprinkler System Compared to Frequencies of the Building

The longitudinal testing on the 16-inch drop yielded natural frequencies of the head and elbow placement directly in line with the buildings natural frequency. The data collected from the 16-inch drop showed one exhibited natural frequency at 15 Hz in the longitudinal plane. During the longitudinal tests of the 12-inch drop the recording at the tee exhibited scattered results while the sprinkler head displayed data portraying a natural frequency peaking at the same time as the buildings natural frequency.

In the transverse test direction the system showed a clear first natural frequency at 10Hz plus or minus half a hertz during the four tests performed. Following that first natural frequency of the sprinkler system the sprinkler line showed acceleration amplification as a result of the buildings resonance input.

Floor Acceleration vs. Acceleration at the Head

The base accelerations used were 0.3 and 0.4g in both directions of testing. The maximum acceleration found from the test in the longitudinal direction was observed in the 16-inch drop at 5g while the model shock from a base input of 0.4g. The maximum acceleration at the head of the 12-inch drop was 4g with the base input 0.4g.

Testing in the transverse direction yielded a maximum acceleration of 16g at the head of the 16-inch drop. The 12-inch drop experienced accelerations of up to 5g when testing at 0.4g.

Amplification Observed

The amplification of the acceleration at the base to the accelerations recorded at the head was from 10 to 40 times. The amplification of the sprinkler drop over the input acceleration from the building in the longitudinal direction is about 1.5 times at the 16-inch drop and zero at the 12-inch drop. In the transverse direction the both drops experienced amplification about 2 times over the buildings accelerations.

Frequencies of the Test Design Compared to the SAP2000 Results

The computer analysis identified the first model frequencies observed during testing. SAP2000 also identified a second mode shape in both test directions, included in the data as expected second modes.

RESULTS FROM STEEL SPRINKLER SYSTEM TESTING

Table 3 Tabulated Results From Steel Sprinkler Testing

Test Direction	Recording Location	Excited Frequency Ranges (Hz)	Highest Amplification	Sap2000 Fundamental Frequencies (Hz)
Longitudinal	12” drop	13-16	10 x	14.2, 45.2
	16” drop	13-16	13 x	
Transverse	12” drop	8-13, 15-17, 18-20	13 x	13.1, 29.8
	16” drop	9-14, 18-21	35 x	

The end of the sprinkler system acted like a cantilever out from the seismic brace. During longitudinal testing the seismic brace absorbed all the moments imposed upon it from the two sprinkler drops. The design of the brace allowed for flexibility by having moveable joints at both points of contact. During longitudinal testing the visual movement from the seismic brace while the buildings exhibited its mode shape was impressive. The rotation at the brace connection pins allowed the brace to act like a shock absorber and provided a secure attachment for the sprinkler pipe.

The placement of the seismic brace allowed the sprinkler line to rotate freely in the transverse direction. The accelerations recorded during transverse testing suggest that the steel sprinkler line had a distinctive first transverse mode shape at ~10Hz. Effects from the buildings excitement were represented in the sprinkler drop data. The buildings amplification is greatest along the upper rafters where the seismic brace is bolted. The building accelerations were observed to amplify through the drops as the sprinkler heads acted as weighted cantilevers being shock from a fixed end.

Because of the interference from the seismic brace, longitudinal acceleration for a sprinkler section securely attached to the building wasn't available like in the CPVC tests. The test of the 16-inch drop shows equal accelerations from both ends of the drop. This suggests the stiffness of the drop causes the entire drop to amplify with the amplification of the building alone. Amplifications observed in the longitudinal tests come from the amplification of the building alone. The recorded amplification of 10 times greater than the base is consistent with amplification previously recorded along the roof ridge of the building.

The excitation of the seismic brace induces acceleration data to scramble. Visually the area at the top of the 12-inch drop is rattling violently while the seismic brace securely fixes the sprinkler line. Longitudinal data from the tee shows up like background noise and is included in the graphs just to show that action in the area existed.

No failure occurred in the Steel Sprinkler system during the shake tests.

9 CONCLUSION

1. Each of the sprinkler designs tested performed without any failures. Amplitudes of the recorded accelerations suggest that forces were present that could have failed an improperly attached support. The visual responses as well as the data collected during testing showed high levels of accelerations present.
2. The highest level of acceleration recorded was at the head on the 12-inch drop of CPVC design 3. The acceleration developed was 26g when the system was resonating from the base level acceleration of 0.5g. The largest amplification of sixty times over the base level occurred at the same CPVC drop when the test ran in the transverse direction at 0.4g.
3. The CPVC sprinkler systems developed large amplifications and remained completely elastic. The extreme flexibility of the material along with the high strength of the CPVC glue denotes the likelihood of a properly secured CPVC sprinkler system failing before the building to be slim to none.
4. Each sprinkler system tested experienced amplification over the base acceleration input, as well as over the buildings own amplification. Each sprinkler design was bolted to peak of the building's roof, where the buildings own amplification was recorded at ten times the base level. When comparing the accelerations in the sprinkler line to those delivered by the building, the CPVC systems were found to have amplification of three to five times above, and the steel sprinkler system shows amplifications two to three times above the building's own amplification.
5. In some sections of the design the sprinkler systems included a high degree of flexibility. In these loose sections the natural mode shapes were witnessed at a

frequency less than when the building became excited. In cases where the sprinkler systems were securely attached to the building, the natural frequencies tested were close to identical to the building's own natural frequencies. Testing showed securely fixed sprinkler systems experience amplification when the building it's attached to resonates.

6. Had the sprinkler drops been restricted by any obstacle damage would have likely occurred from impact pounding. Code allows membranes like gypsum board to surround sprinkler pipes since they fail easily before the sprinkler does. Since gypsum board fails by crushing it would likely act to cushion the sprinkler head movement. With solid objects in the way of a sprinkler line, damage is likely to create potential failures to the system. For each sprinkler design tested there was no interference to sprinkler system movement.
7. The largest unsupported drop tested was 16 inches long. Drops were shown to have the highest level of amplification. These amplifications developed due to the sprinkler heads freedom to move. Current sprinkler designs often have greater drop lengths than 16 inches and should be expected to develop high accelerations during an earthquake. If moment forces get high enough at a fixed end, cases of sheer failure can occur at the threaded connection. Because of the flexibility of CPVC moment forces would have to be extreme to cause a shear failure. As long as CPVC sprinkler systems are glued correctly designs appear to be indestructible in the light of acceleration forces.
8. Code requirements are in place to ensure sprinklers are installed securely on a structure. When a structure moves, the code emphasizes ample clearance along with

flexibility of joints to prevent sprinkler failing before the building. Test performed by the model in this report demonstrate how code approved sprinkler designs remain intact while the building shakes.

9. Reducing the flexibility within the sprinkler system by securely fixing sections to the building caused the system to respond to the building's natural frequency. In CPVC sprinkler design 2, the 16-inch drop had a large degree of flexibility, which gave it a natural mode shape independent from the buildings. By fixing the 16-inch drop to the building, amplification during testing was greatly reduced. If the sprinkler system is completely supported and given proper clearance it will perform as well as the structure during an earthquake.

10 POTENTIAL FOR FUTURE RESEARCH

Further research into the seismic properties of sprinkler systems can be taken in two pathways:

1. Larger more complicated sprinkler systems can be tested to witness shaking effects in different sized components. A room-size model should provide enough space to plumb many different sprinkler designs. A model with multiple floors could test how flexible couplings react at the floor interface. The greatest aid in collecting data would be the availability of multiple recording inputs. With more recording inputs more of the system can be represented for each dynamic test. With enough available inputs the model structure should also be sampled in each test in order to observe any structural changes.
2. Effects on a room’s non-structural interior from a dynamic sprinkler system can be researched. In a room-size model multiple interior objects can be studied to observe the interaction to a dynamic sprinkler system. Potential items are gypsum board, dropped ceiling grids, mechanical equipment, etc.

   The new 10’ x 10’ shake table at Cal Poly is the right platform to test a room size model. A two-story model can be attached to test the effects of inter-story drift on a sprinkler system.

REFERENCES

NFPA-13 1999 edition: *Installation of Fire Sprinkler Systems*, Published by The National Fire Protection Agency

Northridge Earthquake January 17, 1994, *A report on the performance and damage associated with automatic fire sprinkler systems resulting from the Northridge Earthquake (6.7 magnitude) of January 17, 1994 and subsequent aftershocks. A joint cooperative effort for better fire protection by the National Fire Sprinkler Association, inc. and the U.A. Sprinkler Fitters Local 709 and U.A. Local 709 Employers.*, Published by The Fire Sprinkler Advisory Board of Southern California

Tolco's OSHPD (Office of Statewide Health Planning and Development) Pre-approved Seismic Restraint Catalog, Revised version 2/3/99, *For Mechanical, Electrical and Fire Sprinkler Piping*, Published by Tolco incorporated

Angel City Fire Protection - Fire Sprinkler Facts, http://www.angelcityfire.com

Contacts that provided support for the creation of the sprinkler systems:

Wayco Fire Protection Inc.
763 Alphonso Street
San Luis Obispo, CA 93401

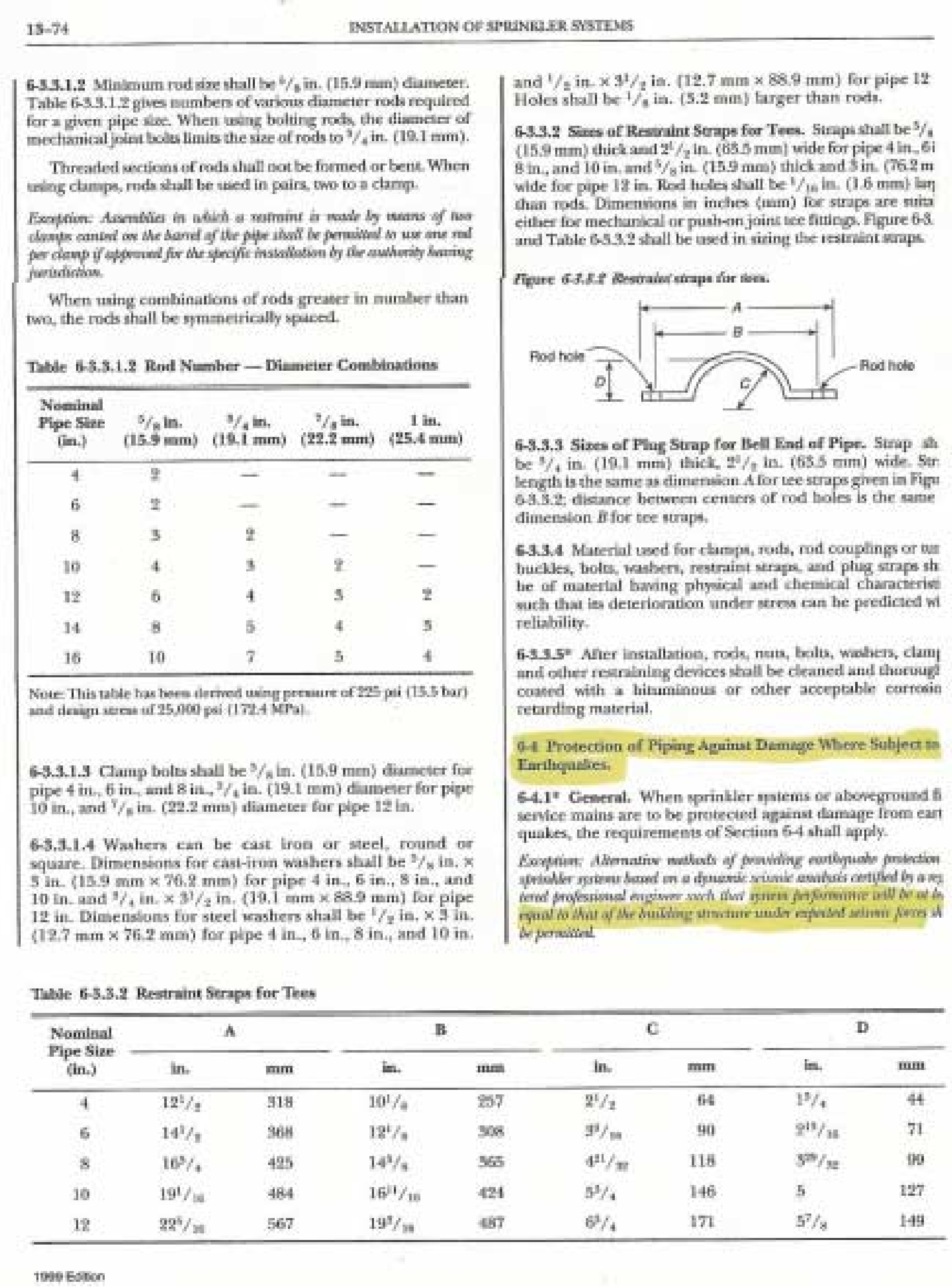
Alpha Fire Protection Corporation
650 Sweeney Lane
San Luis Obispo, CA 93401

Grinnell Fire Protection Systems attn: Chuck in Dublin office

Tolco inc. Fire protection system services attn: Jamie Shaughnessy in San Jose office

APPENDIX

NFPA-13 1999 SEISMIC CODE 6-4



6-3.3.1.2 Minimum rod size shall be $^5/_8$ in. (15.9 mm) diameter. Table 6-3.3.1.2 gives numbers of various diameter rods required for a given pipe size. When using bolting rods, the diameter of mechanical joint bolts limits the size of rods to $^3/_4$ in. (19.1 mm).

Threaded sections of rods shall not be formed or bent. When using clamps, rods shall be used in pairs, two to a clamp.

Exception: Assemblies in which a restraint is made by means of two clamps canted on the barrel of the pipe shall be permitted to use one rod per clamp if approved for the specific installation by the authority having jurisdiction.

When using combinations of rods greater in number than two, the rods shall be symmetrically spaced.

Table 6-3.3.1.2 Rod Number — Diameter Combinations

Nominal Pipe Size (in.)	$^5/_8$ in. (15.9 mm)	$^3/_4$ in. (19.1 mm)	$^7/_8$ in. (22.2 mm)	1 in. (25.4 mm)
4	2	—	—	—
6	2	—	—	—
8	3	2	—	—
10	4	3	2	—
12	6	4	3	2
14	8	5	4	3
16	10	7	5	4

Note: This table has been derived using pressure of 225 psi (15.5 bar) and design stress of 25,000 psi (172.4 MPa).

6-3.3.1.3 Clamp bolts shall be $^5/_8$ in. (15.9 mm) diameter for pipe 4 in., 6 in., and 8 in., $^3/_4$ in. (19.1 mm) diameter for pipe 10 in., and $^7/_8$ in. (22.2 mm) diameter for pipe 12 in.

6-3.3.1.4 Washers can be cast iron or steel, round or square. Dimensions for cast-iron washers shall be $^5/_8$ in. × 3 in. (15.9 mm × 76.2 mm) for pipe 4 in., 6 in., 8 in., and 10 in. and $^3/_4$ in. × $3^1/_2$ in. (19.1 mm × 88.9 mm) for pipe 12 in. Dimensions for steel washers shall be $^1/_2$ in. × 3 in. (12.7 mm × 76.2 mm) for pipe 4 in., 6 in., 8 in., and 10 in. and $^1/_2$ in. × $3^1/_2$ in. (12.7 mm × 88.9 mm) for pipe 12 Holes shall be $^1/_8$ in. (3.2 mm) larger than rods.

6-3.3.2 Sizes of Restraint Straps for Tees. Straps shall be $^5/_8$ (15.9 mm) thick and $2^1/_2$ in. (63.5 mm) wide for pipe 4 in., 6 i 8 in., and 10 in. and $^5/_8$ in. (15.9 mm) thick and 3 in. (76.2 m wide for pipe 12 in. Rod holes shall be $^1/_{16}$ in. (1.6 mm) lar than rods. Dimensions in inches (mm) for straps are suita either for mechanical or push-on joint tee fittings. Figure 6-3. and Table 6-3.3.2 shall be used in sizing the restraint straps.

Figure 6-3.3.2 Restraint straps for tees.

6-3.3.3 Sizes of Plug Strap for Bell End of Pipe. Strap sh be $^3/_4$ in. (19.1 mm) thick, $2^1/_2$ in. (63.5 mm) wide. Str length is the same as dimension *A* for tee straps given in Figu 6-3.3.2; distance between centers of rod holes is the same dimension *B* for tee straps.

6-3.3.4 Material used for clamps, rods, rod couplings or tur buckles, bolts, washers, restraint straps, and plug straps sh be of material having physical and chemical characterist such that its deterioration under stress can be predicted wi reliability.

6-3.3.5* After installation, rods, nuts, bolts, washers, clam and other restraining devices shall be cleaned and thoroug coated with a bituminous or other acceptable corrosio retarding material.

6-4 Protection of Piping Against Damage Where Subject to Earthquakes.

6-4.1* General. When sprinkler systems or aboveground fi service mains are to be protected against damage from ear quakes, the requirements of Section 6-4 shall apply.

Exception: Alternative methods of providing earthquake protection sprinkler systems based on a dynamic seismic analysis certified by a re tered professional engineer such that system performance will be at le equal to that of the building structure under expected seismic forces sh be permitted.

Table 6-3.3.2 Restraint Straps for Tees

Nominal Pipe Size (in.)	A		B		C		D	
	in.	mm	in.	mm	in.	mm	in.	mm
4	$12^1/_2$	318	$10^1/_8$	257	$2^1/_2$	64	$1^3/_4$	44
6	$14^1/_2$	368	$12^1/_8$	308	$3^9/_{16}$	90	$2^{13}/_{16}$	71
8	$16^3/_4$	425	$14^3/_8$	365	$4^{21}/_{32}$	118	$3^{29}/_{32}$	99
10	$19^1/_{16}$	484	$16^{11}/_{16}$	424	$5^3/_4$	146	5	127
12	$22^5/_{16}$	567	$19^3/_{16}$	487	$6^3/_4$	171	$5^7/_8$	149

6-4.2* Couplings. Listed flexible pipe couplings joining grooved end pipe shall be provided as flexure joints to allow individual sections of piping $2^{1}/_{2}$ in. (64 mm) or larger to move differentially with the individual sections of the building to which it is attached. Couplings shall be arranged to coincide with structural separations within a building. Systems having more flexible couplings than required here shall be provided with additional sway bracing as required in 6-4.5.3, Exception No. 4. The flexible couplings shall be installed as follows:

(1) Within 24 in. (610 mm) of the top and bottom of all risers.

Exception No. 1: In risers less than 3 ft (0.9 m) in length, flexible couplings are permitted to be omitted.

Exception No. 2: In risers 3 to 7 ft (0.9 to 2.1 m) in length, one flexible coupling is adequate.

(2) *Within 12 in. (305 mm) above and within 24 in. below the floor in multistory buildings. When the flexible coupling below the floor is above the tie-in main to the main supplying that floor, a flexible coupling shall be provided on the vertical portion of the tie-in piping.

(3) On both sides of concrete or masonry walls within 1 ft of the wall surface.

Exception: Flexible pipe couplings are not required where clearance around the pipe is provided in accordance with 6-4.4.

(4) *Within 24 in. of building expansion joints.

(5) Within 24 in. (610 mm) of the top and bottom of drops to hose lines, rack sprinklers, and mezzanines, regardless of pipe size.

(6) Within 24 in. (610 mm) of the top of drops exceeding 15 ft (4.6 m) in length to portions of systems supplying more than one sprinkler, regardless of pipe size.

(7) Above and below any intermediate points of support for a riser or other vertical pipe.

6-4.3* Seismic Separation Assembly. Seismic separation assemblies with flexible fittings shall be installed where sprinkler piping, regardless of size, crosses building seismic separation joints above ground level.

6-4.4* Clearance. Clearance shall be provided around all piping extending through walls, floors, platforms, and foundations, including drains, fire department connections, and other auxiliary piping.

6-4.4.1 Where pipe passes through holes in platforms, foundations, walls, or floors, the holes shall be sized such that the diameter of the holes is 2 in. (50 mm) larger than the pipe for 1 in. (25 mm) nominal to $3^{1}/_{2}$ in. (89 mm) nominal and 4 in. (100 mm) larger than the pipe for pipe 4 in. (100 mm) nominal and larger. Clearance from structural members not penetrated or used, collectively or independently, to support the piping shall be at least 2 in. (51 mm).

Exception No. 1: Where clearance is provided by a pipe sleeve, a nominal diameter 2 in. (51 mm) larger than the nominal diameter of the pipe is acceptable for pipe sizes 1 in. (25.4 mm) through $3^{1}/_{2}$ in. (89 mm), and the clearance provided by a pipe sleeve of nominal diameter 4 in. (102 mm) larger than the nominal diameter of the pipe is acceptable for pipe sizes 4 in. (102 mm) and larger.

Exception No. 2: No clearance is necessary for piping passing through gypsum board or equally frangible construction that is not required to have a fire resistance rating.

Exception No. 3: No clearance is necessary if flexible couplings are located within 1 ft (0.31 m) of each side of a wall, floor, platform, or foundation.

6-4.4.2 Where required, the clearance shall be filled with a flexible material such as mastic.

6-4.5* Sway Bracing.

6-4.5.1 The system piping shall be braced to resist both lateral and longitudinal horizontal seismic loads and to prevent vertical motion resulting from seismic loads. The structural components to which bracing is attached shall be determined to be capable of carrying the added applied seismic loads.

6-4.5.2 Sway braces shall be designed to withstand forces in tension and compression.

Exception: Tension only bracing systems shall be permitted for use where listed for this service and where installed in accordance with their listing limitations, including installation instructions.*

6-4.5.3 Lateral sway bracing spaced at a maximum interval of 40 ft (12.2 m) on center shall be provided on all feed and cross mains regardless of size and all branch lines and other piping with a diameter of $2^{1}/_{2}$ in. (63.5 mm) and larger. The last length of pipe at the end of a feed or cross main shall be provided with a lateral brace. Lateral braces shall be allowed to act as longitudinal braces if they are within 24 in. (610 mm) of the centerline of the piping braced longitudinally for lines that are $2^{1}/_{2}$ in. (76 mm) and greater in diameter. The distance between the last brace and the end of the pipe shall not exceed 20 ft (6.1 m). This requirement shall not preclude the use of a lateral brace serving as a longitudinal brace as described in this paragraph.

Exception No. 1: Where the spacing of lateral braces is permitted to be up to 50 ft (7.6 m), the distance between the last brace and the end of the pipe is permitted to be extended to 25 ft (15.2 m).

Exception No. 2: Lateral sway bracing shall not be required on pipes individually supported by rods less than 6 in. (152 mm) long measured between the top of the pipe and the point of attachment to the building structure.

Exception No. 3: U-type hooks of the wraparound type or those U-type hooks arranged to keep the pipe tight to the underside of the structural element shall be permitted to be used to satisfy the requirements for lateral sway bracing provided the legs are bent out at least 30 degrees from the vertical and the maximum length of each leg and the rod size satisfies the conditions of Table 6-4.5.8.

Exception No. 4: Where flexible couplings are installed on mains other than as required in 6-4.2, a lateral brace shall be provided within 24 in. (610 mm) of every other coupling, but not more than 40 ft (12 m) on center.

Exception No. 5: Where building primary structural members exceed 40 ft (12 m) on center, lateral braces shall be permitted to be spaced up to 50 ft (15.2 m) on center.

6-4.5.4 Longitudinal sway bracing spaced at a maximum of 80 ft (24 m) on center shall be provided for feed and cross mains. Longitudinal braces shall be permitted to serve as lateral braces where they are installed within 24 in. (609 mm) of the piping that is braced laterally. The distance between the last brace and the end of the pipe shall not exceed 40 ft (12.2 m).

6-4.5.5* Tops of risers shall be secured against drifting in any direction, utilizing a four-way sway brace.

6-4.5.6* Horizontal loads for braces shall be determined by analysis based on a horizontal force of $F_p = 0.5\ W_p$, where F_p is the horizontal force factor and W_p is the weight of the water-filled piping. For lateral braces, the load shall include all branch lines and mains, unless the branch lines are provided with longitudinal bracing, within the zone of influence of the brace. For longitudinal braces, the load shall include all mains within the zone of influence of the brace.

Exception: Where the use of other horizontal force factors is required or permitted by the authority having jurisdiction, they shall take precedence.

6-4.5.7 Where the horizontal force factors used exceed 0.5 W_p and the brace angle is less than 45 degrees from vertical or where the horizontal force factor exceeds 1.0 W_p and the brace angle is less than 60 degrees from vertical, the braces shall be arranged to resist the net vertical reaction produced by the horizontal load.

6-4.5.8* Sway bracing shall be tight. For individual braces, the slenderness ratio (l/r) shall not exceed 300 where l is the length of the brace and r is the least radius of gyration. Where threaded pipe is used as part of a sway brace assembly, it shall not be less than Schedule 30. All parts and fittings of a brace shall lie in a straight line to avoid eccentric loadings on fittings and fasteners. For longitudinal braces only, the brace shall be permitted to be connected to a tab welded to the pipe in conformance with 3-6.2. For individual braces, the slenderness ratio, l/r, shall not exceed 300 where l is the length of the brace and r is the least radius of gyration. For tension-only braces, two tension-only brace components opposing each other must be installed at each lateral or longitudinal brace location. For all braces, whether or not listed, the maximum allowable horizontal load shall be based on the weakest component of the brace with safety factors. The loads determined in 6-4.5.6 shall not exceed the lesser of the maximum allowable loads provided in Table 6-4.5.8 or the manufacturer's certified maximum allowable horizontal loads for 30- to 44-degree, 45- to 59-degree, 60- to 89-degree, and 90-degree brace angles. These certified allowable horizontal loads must include a minimum safety factor of 1.5 against the ultimate break strength of the brace components and then be further reduced according to the brace angles.

Exception: Other pipe schedules and materials not specifically included in Table 6-4.5.8 shall be permitted to be used if certified by a registered professional engineer to support the loads determined in accordance with the above criteria. Calculations shall be submitted where required by the authority having jurisdiction.

Table 6-4.5.8 Maximum Horizontal Loads for Sway Braces

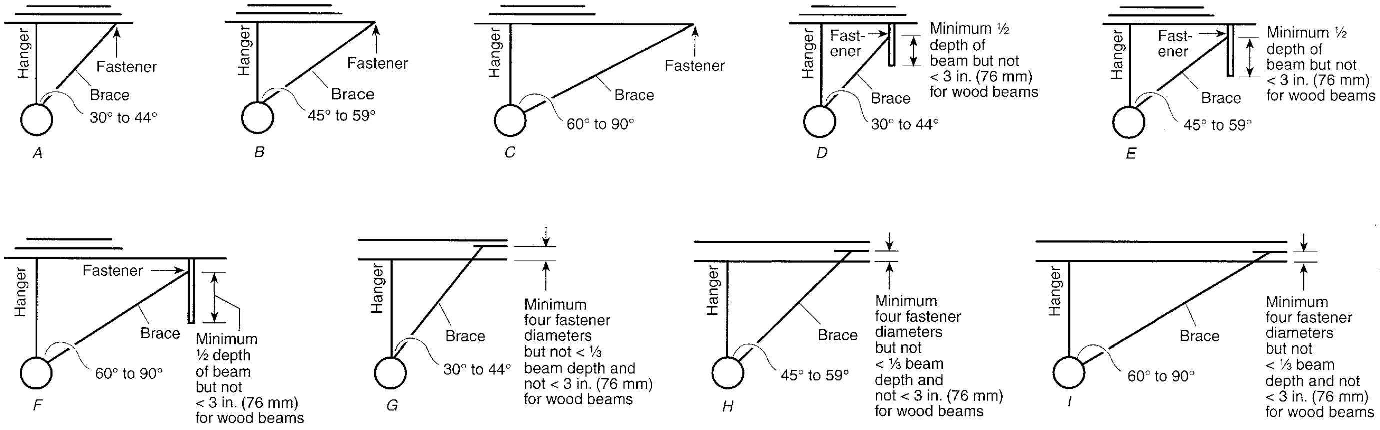
			Maximum Horizontal Load (lb)		
Shape and Size	**Least Radius of Gyration**	**Maximum Length for:**	**30°–44° Angle from Vertical**	**45°–59° Angle from Vertical**	**60°–90° Angle from Vertical**
Pipe (Schedule 40)	$= \frac{\sqrt{r_o^2 + r_i^2}}{2}$	$l/r = 100$			
1 in.	0.42	7 ft 0 in.	1,767	2,500	3,061
$1^{3}/_{4}$ in.	0.54	9 ft 0 in.	2,392	3,385	4,145
$1^{1}/_{2}$ in.	0.54	10 ft 4 in.	2,858	4,043	4,955
2 in.	0.787	13 ft 1 in.	3,828	5,414	6,630
Angles		$l/r = 200$			
$1^{1}/_{2} \times 1^{1}/_{2} \times {}^{3}/_{4}$ in.	0.292	4 ft 10 in.	2,461	3,481	4,263
$2 \times 2 \times {}^{1}/_{4}$ in.	0.391	6 ft 6 in.	3,356	4,746	5,813
$2^{1}/_{2} \times 2 \times {}^{1}/_{4}$ in.	0.424	7 ft 0 in.	3,792	5,363	6,569
$2^{1}/_{2} \times 2^{1}/_{2} \times {}^{1}/_{4}$ in.	0.491	8 ft 2 in.	4,257	6,021	7,374
$3 \times 2^{1}/_{2} \times {}^{1}/_{4}$ in.	0.528	8 ft 10 in.	4,687	6,628	8,118
$3 \times 3 \times {}^{1}/_{4}$ in.	0.592	9 ft 10 in.	5,152	7,286	8,923
Rods	$= \frac{r}{2}$	$l/r = 200$			
${}^{3}/_{8}$ in.	0.094	1 ft 6 in.	395	559	685
${}^{1}/_{2}$ in.	0.125	2 ft 6 in.	702	993	1,217
${}^{5}/_{8}$ in.	0.156	2 ft 7 in.	1,087	1,537	1,883
${}^{3}/_{4}$ in.	0.188	3 ft 1 in.	1,580	2,235	2,737
${}^{7}/_{8}$ in.	0.219	3 ft 7 in.	2,151	3,043	3,726

Table 6-4.5.8 Maximum Horizontal Loads for Sway Braces *(Continued)*

			Maximum Horizontal Load (lb)		
Shape and Size	**Least Radius of Gyration**	**Maximum Length for:**	**30°–44° Angle from Vertical**	**45°–59° Angle from Vertical**	**60°–90° Angle from Vertical**
Flats	= 0.29*h* (where *h* is smaller of two side dimensions)	$l/r = 200$			
1½ × ¼ in.	0.0725	1 ft 2 in.	1,118	1,581	1,936
2 × ¼ in.	0.0725	1 ft 2 in.	1,789	2,530	3,098
2 × ⅜ in.	0.109	1 ft 9 in.	2,683	3,795	4,648
Pipe (Schedule 40)	$= \frac{\sqrt{r_0^2 + r_i^2}}{2}$	$l/r = 100$			
1 in.	0.42	3 ft 6 in.	7,068	9,996	12,242
1¼ in.	0.54	4 ft 6 in.	9,567	13,530	16,570
1½ in.	0.623	5 ft 2 in.	11,441	16,181	19,817
2 in.	0.787	6 ft 6 in.	15,377	21,746	26,634
Rods	$= \frac{r}{2}$	$l/r = 100$			
⅜ in.	0.094	0 ft 9 in.	1,580	2,234	2,737
½ in.	0.125	1 ft 0 in.	2,809	3,972	4,865
⅝ in.	0.156	1 ft 3 in.	4,390	6,209	7,605
¾ in.	0.188	1 ft 6 in.	6,322	8,941	10,951
⅞ in.	0.219	1 ft 9 in.	8,675	12,169	14,904
Pipe (Schedule 40)	$= \frac{\sqrt{r_o^2 + r_i^2}}{2}$	$l/r = 300$			
1 in.	0.42	10 ft 6 in.	786	1,111	1,360
1½ in.	0.54	13 ft 6 in.	1,063	1,503	1,841
1½ in.	0.623	15 ft 7 in.	1,272	1,798	2,202
2 in.	0.787	19 ft 8 in.	1,666	2,355	2,885
Rods	$= \frac{r}{2}$	$l/r = 300$			
⅜ in.	0.094	2 ft 4 in.	176	248	304
½ in.	0.125	3 ft 1 in.	312	441	540
⅝ in.	0.156	3 ft 11 in.	488	690	845
¾ in.	0.219	5 ft 6 in.	956	1,352	1,656

Figure 6-4.5.9 Maximum loads for various types of structure and maximum loads for various types of fasteners to structure.

Note: Loads (given in pounds) are keyed to vertical angles of braces and orientation of connecting surface. These values are based on concentric loadings of the fastener. Use figures to determine proper reference within table. For angles between those shown, use most restrictive case. Braces should not be attached to light structure members.



Note: For wooden beams not less than 3 in. (76 mm).

Lag Screws and Lag Bolts in Wood (Load Perpendicular to Grain — Holes Predrilled Using Good Practice)

Shank Diameter of Lag (in.)

		⅜									½									⅝									⅞								
		A	B	C	D	E	F	G	H	I	A	B	C	D	E	F	G	H	I	A	B	C	D	E	F	G	H	I	A	B	C	D	E	F	G	H	I
Length under head (in.)	3	304	325	292	168	325	526	230	324	400	366	—	—	—	—	632	—	—	—	410	—	—	—	—	716	—	—	—	487	—	—	—	—	843	—	—	—
	4	392	354	317	183	354	678	250	352	435	473	509	456	264	509	818	360	507	626	538	—	—	—	—	929	—	—	—	548	—	—	—	—	1122	—	—	—
	5	476	375	336	194	375	824	265	373	461	582	545	488	282	545	1008	385	542	670	687	728	653	277	728	1154	515	725	896	813	—	—	—	—	1407	—	—	—
	6	564	382	342	196	382	976	270	380	470	689	559	501	288	559	1192	395	556	687	791	778	697	403	778	1360	550	775	957	971	—	—	—	—	1630	—	—	—
	8	—	—	—	—	—	—	—	—	—	905	573	513	296	573	1586	405	570	704	1044	806	723	416	806	1807	570	803	991	1297	1365	1223	685	1365	2244	965	1359	1678

For SI units, 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb = 0.45 kg.

Figure 6-4.5.9 *(Continued)*

Through Bolts in Wood (Load Perpendicular to Grain)

Diameter of Bolt (in.)

		⅜						½						⅝						⅞					
		ABCE	D	F	G	H	I	ABCE	D	F	G	H	I	ABCE	D	F	G	H	I	ABCE	D	F	G	H	I
Length of Bolt in Timber (in.)	1½	300	173	519	150	211	261	340	197	589	170	239	296	390	225	675	195	275	339	470	272	614	235	331	409
	2	370	214	641	185	261	322	420	243	727	210	296	365	470	272	814	235	331	409	580	335	1004	290	408	504
	2½	460	266	796	230	324	400	550	318	952	275	387	478	620	358	1074	310	437	539	760	439	1316	380	535	661
	3	480	277	831	240	338	417	630	364	1091	315	444	548	710	410	1229	355	500	617	870	503	1506	435	613	757
	3⅝	460	268	797	230	324	400	720	416	1247	360	507	626	850	491	1472	425	599	739	1050	607	1818	525	739	913
	5½	—	—	—	—	—	—	680	393	1177	340	479	591	1020	590	1766	510	718	887	1580	913	2736	790	1113	1374

For SI units, 1 in. = 25.4 mm; 1 lb = 0.45 kg.

Expansion Shields in Concrete

Diameter of Bolt (in.)

		⅜									½									⅝									⅞								
		A	B	C	D	E	F	G	H	I	A	B	C	D	E	F	G	H	I	A	B	C	D	E	F	G	H	I	A	B	C	D	E	F	G	H	I
Min. Depth of Hole (in.)	2½	498	962	1173	678	668	860	925	1303	1609	—	—	—	—	—	—	1638	2306	2848	—	—	—	—	—	—	2080	2930	3617	—	—	—	—	—	—	2470	4113	5078
	3¼	—	—	—	—	—	—	925	1303	1609	923	1782	2076	1200	1782	1597	1638	2306	2848	—	—	—	—	—	—	2080	2930	3617	—	—	—	—	—	—	2970	4113	5078
	3¾	—	—	—	—	—	—	925	1303	1609	—	—	—	—	—	—	1638	2306	2848	1480	2857	2637	1524	2857	2581	2080	2930	3617	—	—	—	—	—	—	2970	4113	5078
	4½	—	—	—	—	—	—	925	1303	1609	—	—	—	—	—	—	1638	2306	2848	—	—	—	—	—	—	2080	2930	3617	3070	4130	3702	2139	4130	5312	2970	4113	5078

For SI units, 1 in. = 25.4 mm; 1 lb = 0.45 kg.

Connections to Steel (Values Assume Bolt Perpendicular to Mounting Surface)

Diameter of Unfinished Steel Bolt (in.)

¼									⅜									½									⅝								
A	B	C	D	E	F	G	H	I	A	B	C	D	E	F	G	H	I	A	B	C	D	E	F	G	H	I	A	B	C	D	E	F	G	H	I
400	500	600	300	500	650	325	458	565	900	1200	1400	800	1200	1550	735	1035	1278	1600	2050	2550	1450	2050	2850	1300	1830	2260	2500	3300	3950	2250	3300	4400	2045	2880	3557

For SI units, 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb = 0.45 kg.